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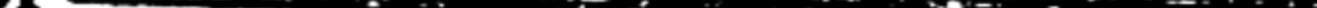
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ATOMS AND ATOMIC ENERGY

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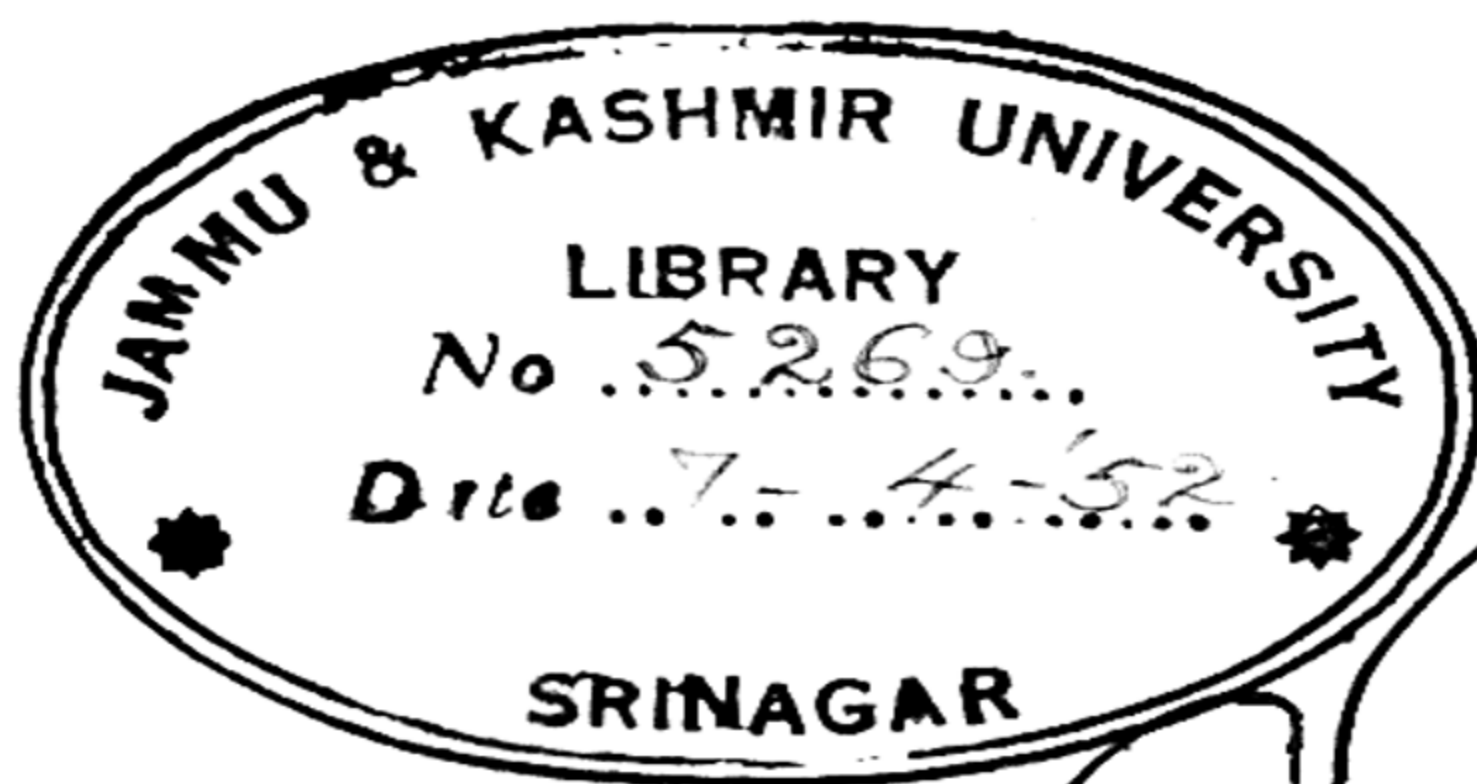
A Simple Explanation

by

R. W. HALLOWS

T.D., M.A.Cantab, M.I.E.E.

*Member, Société des Ingénieurs
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Author's Preface

MOST OF THE BOOKS now available on the subject of atoms and atomic energy have been written by eminent physicists and mathematicians. That, perhaps, is why many of them are so difficult for ordinary people to understand. I am not a physicist, not very good at mathematics and certainly not eminent; but I have for long been intensely interested in the unfolding of this most fascinating of detective stories, the investigation of the mystery of the atom and of the possibility of harnessing the energy bound up in it.

To follow the thrilling developments of the story meant slogging through text-books, attending lectures and seizing every opportunity of conversing with scientists engaged in atomic research. In order to clarify my own mental pictures I formed the habit of jotting down "translations" into simple language of what I read and heard. These notes were seen from time to time by friends, who suggested that they should be tidied up and made into a book. That is how the present volume came into being. It does not pretend to be a learned work or to contribute any new clues. All that it tries to do is to help the ordinary reader to understand something of the atom and of atomic energy.

The theme of the detective novel is often that plodding, but almost incredibly lame-dog professionals of the C.I.D., are helped over stiles by a gifted amateur. The theme of the present detective story is quite different. The role of the amateur here is to interpret the brilliant work done by the professionals—the physicists, the chemists and the mathematicians—in such a way that the ordinary man and woman can understand it and appreciate it.

It must not be imagined that there is no plodding in the work of the scientists. The truth of the definition of genius as "an infinite capacity for taking pains" was never more completely proved than in the atomic research laboratory. Professor P. M. S. Blackett, for example, made more than 20,000 photographs of one endlessly repeated experiment before the historic picture seen in Plate I was obtained; and there are innumerable other instances of brilliant discoveries made as the results of months, or even years, of hard, monotonous labour. It needs the brain of a scientist of the calibre of Sir Ernest Rutherford (afterwards Lord Rutherford) to realise that immense series of experiments are worth while; to feel no discouragement if result after result is negative; to seize upon any tiny clue and to see its value; to grasp just what it means and to what further developments it may lead when finally the result, long hoped for, is obtained. Christian names are often misfits; Rutherford's was not.

The mystery of the atom has not yet been fully fathomed, though recent progress has been enormously rapid. We know enough now to realise that the way in which Man decides to utilise atomic energy may make or mar the whole future of human civilisation. The problem of the atom is thus one which closely concerns everyone. In the pages which follow I have endeavoured to tell the story of the atom and of atomic energy in simple language, so that the reader may judge for himself what has already been done and may have some inkling of what the future may bring. It is a story as thrilling as that of the unravelling of any crime mystery by detectives. And, unlike the detective tale, it is a real life story in which the reader is intimately concerned.

R. W. H.

Notes

(1) The drawings are numbered according to the chapters to which they belong. Thus Fig. VII, 3, is the third illustration to Chapter VII.

(2) Only a few of the simplest kinds of apparatus used in the atomic laboratory are described in the text. Those who desire descriptions of some of the more complex devices will find these in Appendix (A).

(3) The hydrogen bomb is discussed in Appendix (C).

Contents

CHAP.	PAGE
I. The Detective Methods of Science	I
II. What is Matter?	6
III. Clue follows Clue	18
IV. Fresh Trails	28
V. Chemists as Detectives	45
VI. Rutherford attacks the Problem	59
VII. Different kinds of the Same Thing	68
VIII. The Orbiting Electrons and Radiation	79
IX. Something about the Nucleus	88
X. Radio-activity	94
XI. From the Depths of Outer Space	111
XII. Chain Reactions (1)	118
XIII. Chain Reactions (2)	126
XIV. The Atomic Bomb	134
XV. Controlled Energy from the Atom (1)	141
XVI. Controlled Energy from the Atom (2)	149
XVII. What does the New "Fuel" offer?	154
XVIII. Useful By-products	161
XIX. Looking Ahead	166
XX. Conclusion	170
<i>Appendix</i> (A) Tools of the Trade	173
(B) Periodic Table of the Elements	188
(C) The Hydrogen Bomb	190
<i>Index</i>	195

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List of Plates

(Between pp. 100–101)

- I. Cloud chamber photograph showing disruption of nitrogen bomb
- II. Cloud chamber photographs. Collision between an alpha-particle and helium and oxygen atoms
- III. The New Mexico atomic bomb explosion 0·016 seconds after detonation
- IV. The New Mexico atomic bomb explosion 0·053 seconds after detonation
- V. Aerial photograph of the site of the New Mexico atomic bomb explosion
- VI. General view of one face of 'Gleep'
- VII. Van de Graaf high voltage generator
- VIII. The production of radio-active isotopes

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CHAPTER I

The Detective Methods of Science

THERE ARE SOME scoffers who try to maintain that, despite all their talk, the long words that they use and the claims that they make, scientists really know very little. "Almost as soon as one man announces a new theory," such people say, "someone else comes to prove that he is all wrong and to advance an entirely different theory. Glance through almost any scientific text-book more than a dozen years or so old and you are more than likely to find that a good many of the statements made by its writer have since been exploded and shown to be false. Can one take seriously any branch of so-called knowledge in which the 'facts' of to-day are shown to-morrow to be mere fiction?"

This attitude is understandable, even though it contains a fundamental misconception. Every real scientist realises to the full the limitations of human knowledge in his day. More than two thousand years ago the philosopher Socrates claimed to be the wisest of men because he knew that he *knew* nothing. The position of the modern scientist may perhaps be summed up in the following way: "We know that some of our basic principles are true because they are derived from direct observation and measurement; because they have been checked, counterchecked and checked again: because they have stood up to every test to which they have been put. Other principles we hold to be true because, though they are the results of calculation and deduction rather than direct measurement and observation, they fit in exactly with all the data in our possession; because they fully explain things for which no

other satisfactory explanations can be found; because they remain unshaken by any tests that we have been able to devise. We do not assert that principles of this latter kind are beyond all question true and certain, any more than we claim that human knowledge is complete. We know very well that human knowledge is far from being complete and that no day passes without adding something to it. It may well be that the increased knowledge of the future will show that some of the 'truths' calculated and deduced to-day are but half truths—or even not true at all. All that and more may take place. If a truth is defined as something which has not been shown to be false and cannot be shown to be false in the light of all the facts now at our disposal, then these principles are truths. If, on the other hand, a truth is held to be something which can never by any possibility be disproved, then these principles are not truths; they are the nearest approach that can now be made to what all the clues available indicate as the solutions of mysteries which have hitherto baffled man's intelligence."

In writing a textbook, a scientist cannot qualify every statement by such words as "so far as we know at present"; but that is what he really means when he may appear to be laying down fixed and immutable laws. Human knowledge is continually growing and growth implies change. What we understand by a truth is something which accords entirely with all the known facts and cannot be disproved by any method that man's intelligence can devise. A truth remains a truth so long as these conditions are fulfilled.

Euclid was not telling a lie when he stated that parallel straight lines never meet, however far they are produced in either direction; nor were those who for centuries passed on his teaching. It was the truth and it remained the truth until comparatively recently. Our present truth

is that such lines do meet if they are produced to infinity. No one can say what the truth in this instance will be a thousand years from now.

The scientist's approach to any problem with which he is confronted is like that of Sherlock Holmes, or Lord Peter Wimsey, or Poirot, or any of the great detectives of fiction or real life. He first of all assembles all the cast-iron facts concerning the case that he can get hold of. Next he forms his first theory to fit in with every one of the then known clues. The first theory may be merely tentative. That does not matter, for it stimulates his brain and those of his assistants. Further evidence may be needed to substantiate it; if so, every effort must be concentrated on finding that evidence. Possibly, the desired evidence is not forthcoming. The first theory must be discarded—in other words, one possible explanation is ruled out. But there must be an explanation and the shortcomings of the first theory have already suggested a fresh one. The discovery of new clues leads to the discarding of one theory and the building up of another. Suspicion may turn out again and again to have been wrongly directed; but not until it appears that a clear case has been made out is an arrest made by the detective or a fact accepted by science.

Another parallel is to be found in athletic and other sporting records. Fifty years ago no one had ever run 100 yards in less than 9.4 seconds. The fact that that was then the best time for the distance did not mean that it was the best that could ever be done; it meant that it was the best of which any individual human body had so far proved itself capable. That time has been equalled or beaten by many men since then, and to-day the record stands at 9.2 seconds. A day must eventually come when some runner will return a time which is the absolute best, a record which can never be broken, since it will represent

the supreme effort within the powers of the human frame. But it is likely to be long before that happens, and in the meantime finer and finer performances by athletes on the track must lead to the replacement of existing records by new ones. In the same way the improving knowledge, skill and equipment of mathematicians, physicists and chemists are bound to cause old scientific theories to be abandoned in favour of others more in line with new discoveries about the world itself, the living things which inhabit it and the heavenly bodies far away in space.

Though it may be long before the absolute truth, the ultimate truth is reached in many branches of knowledge, each new theory is now, and will be in days to come, the nearest approach to that truth that is possible in the light of the knowledge attained at that time. Like the athlete who has put up a world's record, the scientist whose new theory gains general acceptance no doubt feels that he has accomplished something of note; but he can hardly be surer that his theory is final—the last word on the subject—than can the athlete that his record will never be broken by someone else.

It has happened again and again that just when Man was beginning to think that he was nearing finality in some particular branch of knowledge, a revolutionary discovery has shown him that he really knew far less than he thought: the theory which seemed about to provide the detectives with a complete solution of the great mystery has had to be abandoned in the light of new facts.

The growth of human knowledge is rather like the creeping of successive waves higher and higher up the shore. Sometimes the advance is slow; but there are moments when an unexpectedly big wave carries it notably further. At times it seems that it must soon be high tide; at times that point seems still a long way off. For thousands upon thousands of years the tide of human

knowledge rose slowly. In the past few years there has been a succession of great waves. The tide has come rushing in. But the shore is an unknown one and we cannot tell how far the present waterline is from the high-tide mark.

What is Matter?

IT IS SOMETIMES SUGGESTED that when Nature selected Man as the future head of her animal kingdom she fitted him for the task that lay ahead by showering special gifts upon him; but to me, at any rate, it seems that Nature educated and developed Man in the hardest of hard ways. Far from endowing him with special gifts, she deprived him of most of the "built-in" weapons of attack and defence with which she had furnished other creatures. By animal standards we must admit that Man is a pretty poor thing. His strength is below that of other creatures of comparable size. His sight is good; but the acuteness of his hearing and the range of sounds to which his ears respond are inferior to those of many other animals. Even in the matter of sight he has not the power possessed by the cat, the owl or the rabbit of discerning objects no longer illuminated by the sun; what he is pleased to call pitch darkness is far from being a complete blackout to them. His sense of smell is so feeble that he cannot track friends or enemies by the use of his nose. Nature, in fact, almost entirely removed the nose from his offensive and defensive armoury when she egged him on to walk erect on his hind legs, with the result that the organ in question is normally carried far from the ground.

Other creatures had fangs, tusks, claws, stings and even self-charging electric batteries as part of their equipment. Some of them were given the power to evade their enemies by a turn of speed which enabled them to show the proverbial clean pair of heels; the slower ones were given armour plating, tough hides and shells; or a camouflage

colouring which made it possible then to become almost invisible by melting into their surroundings. Man had none of these things: he had to invent tools, weapons and methods of concealment and defence or be numbered, like the brontosaurus and the pterodactyl, amongst Nature's unsuccessful experiments. True, she had given him hands, which could do all manner of things impossible to paws, hoofs and talons; but only a brain superior to that possessed by other animals could find ways of turning to full account the marvellous possibilities of those hands. The earliest human brain was probably little if any better than those of some of the other animals; but as the hands became more and more adept, the brain by which their movements were directed developed until it grew into something the like of which no other creature possessed.

One of Nature's cleverest strokes was to take away from Man the protection of the thick, hairy pelt which covered his nearest simian relatives from top to toe. He was obliged to invent a detachable pelt, in the form of clothing, which could at will be made lighter or heavier, or discarded altogether. Once Man had invented clothing, his superiority over all other animals was assured. Though they might cope with certain temperature variations by growing thicker coats in winter than in summer, the range of temperatures which could be made endurable in this way was limited. The lower animals, as we are now pleased to call them, had to develop a large number of species, each able to exist in only a small part of the world. Some of those equipped with the power of covering great distances—the birds, for example—extended their range of territory by seasonal migrations. Others, like the dormouse and certain kinds of tropical fish, developed the power of going into a state of semi-suspended animation when seasonal conditions made it impossible for them to

exist in a normal state of activity. But, with his invention of clothing, the artificial pelt which could be adapted at will to all seasons and all climates, Man alone solved the problem of being able to live a normal life, year in, year out in any part of the world where food and water are available.

The next step suggested by the brain, which was now improving rapidly in answer to the increasing use made of it was twofold: hunting for meat could be simplified if some of the "game" animals were captured and domesticated; the winter shortage of vegetable foods could be eliminated by cultivating the plants concerned and finding a means of preserving their products. Farming was born; and with farming came the community and the permanent self-supporting settlement.

Man now no longer spent, as do most of the other animals, the greater part of his time in hunting for food, in devouring it and in the long periods of sleep necessary to work off fatigue and to prepare him for the next food hunt. He began to have leisure; and in leisure he found time for a new process: thought. It must not be imagined that the early men of whom we are thinking had anything like the brains of the average civilised adult of to-day. Probably their minds were on a level with those of very young modern children. Such men had all the inquisitiveness of children; they saw things that puzzled them and they longed to find out about them. To questions such as "Why do things happen?" and "How do things happen?" they could discover no answers in terms of human powers. Ever since Man has had the first glimmerings of thought he has probably been a religious animal, ascribing sunlight, darkness, birth, death, storms, fine weather and other natural manifestations to some great Being, which, having made everything, decided why, when and how events should take place. Early men and their descendants

for thousands of years were content to answer these questions by saying that the great creative Being ordained the reasons for and the times of events and that no mortal could know His purpose or design.

But there was a third question, "What are things made of?" which seemed to involve far less mystery. After all, things were there to touch and see and smell and taste. They seemed to be made of other things, for you could divide a tree into leaves, bark, wood and roots; or the carcase of a slaughtered animal into flesh, bones, blood and a collection of queer-looking internal plumbing. If the Being had made such things, of what had He made them?

We have, of course, no direct records of the conclusions at which these very early men arrived, for writing is a comparatively recent invention. But a great deal can be learnt by examining the age-old legends, the myths, the folk-lore and the fairy tales which were handed down by word of mouth from generation to generation. From these we can see that early men began to conceive rather nebulous ideas of the nature of things, which settled down into the form in which we find them in the oldest Greek philosophers, fragments of whose writings have come down to us. About 3,000 years ago the most learned of men held that all matter was made from combinations of four principles or elements. These were air, earth, water and fire—or, as we should now put it, the gaseous, the solid, the liquid and heat. The living thing was warm; most inanimate things were not; the sun seemed to be connected with growth and fertility, whilst fire could bring both comfort and pain to living things; therefore fire was an element and the sun was a god to be worshipped. Aristotle, who flourished about 350 B.C., still accepted these principles, but added wet and dry as qualifications of them. Thus air was hot and wet; earth, cold and dry; water,

cold and wet; fire, hot and dry. Aristotle was accepted up to the time of the renaissance and even beyond as the unquestioned and unquestionable authority on matters scientific; his views remained unchallenged for centuries. It is interesting to note that, though neither Aristotle nor his followers realised it, the four-element theory contained a clue which pointed the way to the truth, if only its significance had been realised. Heat is a form of energy. One of Einstein's most important theories is that energy is a constituent of all matter; we shall see later that subsequent research has confirmed the truth of this theory again and again.

About a century before Aristotle there lived another Greek thinker who was inspired to suggest a clue to the discovery of the nature of matter which was remarkably close to the truth. This was Democritus of Abdera, who put the question: What will eventually be left if I go on cutting up a piece of, say, lead into smaller and smaller pieces? His answer was that in the end tiny specks of lead would result, so small that each was *a-tomos* or uncuttable. These atoms, he said, are the ultimate minute pieces of lead; they and others like them are the bricks of which all the lead in the world is built up. He was perfectly correct, so far as he went. Lead is composed of lead atoms; iron, of iron atoms and silver, of silver atoms. But (1) wood and sugar and water and hair are not composed of atoms of wood, sugar, hair and water respectively—we shall go more fully into this presently; and (2) the atom is by no means "uncuttable." We could not live if some of the outer parts of millions of atoms were not split off at every breath we draw; the harnessing of atomic energy would be impossible if the inner parts of the atom could not also be broken up.

In the time of Democritus no means existed of proving or disproving the correctness of the atomic theory. Then

and for hundreds of years afterwards the detectives were poorly equipped with instruments and tools. They shelved the atomic theory as being ingenious, but improbable. The four-element theory appeared to offer the most promising line of investigation and for something like two thousand years the inquirers followed a false trail.

During the long dark period before the renaissance European Man and his neighbours were so busily engaged in killing one another or in striving to combat the effects of lawlessness, pestilence and famine that the advance of human knowledge was very much slowed down. There were even times when there was a retrogression, when the generation of the day knew less than its grandfathers had known. For centuries the comparatively small number of men who could read and write and had time for study believed that Aristotle's opinions represented not merely the last word that had been said, but the last word that ever could be said in the realm of natural science. Any views that differed from his were, and always must be, erroneous. Worse than that, they were impious.

The renaissance was not so much a rebirth of learning as a rebirth of freedom of thought. Men began to realise that they could not accept the doctrine that views and opinions good enough for their fathers, their grandfathers and still more distant forbears must be good enough for them. They began to think for themselves; and it was not long before such thinking, coupled with observation and experiment, led them to see that human knowledge was far from having reached finality. No one, it was seen, had satisfactorily answered the question: What are things made of? The hunt was up again. In the newly founded universities, in monasteries and sometimes in their own homes new generations of detectives began to make fresh examinations of old clues and to search for new ones.

An important part in the investigation was played by

the alchemists, despite the derision meted out to them in their own time and afterwards. They were certainly the fathers of modern chemistry, which still uses in its laboratories the test-tubes, the retorts, the beakers, the flasks and other apparatus devised by them. One of their goals was the transmutation of matter; that is to say the finding of a means whereby some cheap and common substance, such as lead, could be transformed in the laboratory into a rare and valuable substance, such as gold. It is, by the way, strange that gold should have played and should still play so important a part in Man's history. Gold does not tarnish, it is extremely ductile and its colour is pleasing. Apart from these things, it has few useful qualities as a metal. It is in request (though much less so than in former years) for the ornamentation of human bodies, furniture and buildings; small amounts are used in dentistry, photography and the making of electrical apparatus—and that is almost the tale of its useful applications, for gold coinage has now virtually ceased to exist in most parts of the world. Yet the desire to possess gold remains so strong that men are more than anxious to exchange things of far greater real value for this metal. It is, perhaps, in keeping with the general mild insanity of the age in which we live that the bulk of the gold wrung to-day by toil and sweat from the bowels of the earth is hurried across the Atlantic to be reburied, further than ever from the light of day, in the vaults of a fortress specially built for the purpose in a remote wilderness in America!

Be that as it may, gold had and still has a high value. The alchemists were persuaded that one day one of them would achieve fame and fortune as the result of successful experiments in transmutation. They were wrong in thinking that transmutation could be effected by any of the processes or the apparatus available to them. But, though

they were laughed at for centuries and their efforts discredited, they had suggested a valuable clue. The first actual transmutation (not of lead into gold, but of two gases into two other gases) was accomplished by Rutherford in 1919.

The alchemists did even more valuable work in forming a new conception of the elements. In their quaint experiments involving unicorn's horn, the jewel in the head of a toad, crocodile's tears and so on they found that there were certain substances which could not be broken down into any simpler form. Amongst these were lead, iron, sulphur, copper, and mercury. The later alchemists and the early chemists abandoned the age-old conception of air, earth and fire as elements. One of the original four "elements" was retained for some time: until Henry Cavendish* (who gave his name to the Cavendish Laboratories at Cambridge, where, under Rutherford and his successors, such wonderful work was later to be done) showed that water could be produced by exploding a mixture of the gases oxygen and hydrogen, water was still thought to be an element.

Cavendish went very much further. He showed that, no matter how the experiment was made, the water produced was always a combination of two volumes of hydrogen with one volume of oxygen. If, to begin with, the vessel in which the explosion took place contained, say, 2 pints of oxygen and 2 pints of hydrogen, he found that all of the hydrogen, but only half of the oxygen went to make the water vapour. The inference was that water was not an element, but a compound: the smallest particle of water must consist of two parts of hydrogen and one of oxygen in close combination.

The later alchemists had come to realise that some substances were elements and others compounds of

* 1731-1810.

elements. They defined an element as something which could not be reduced to any simpler form. That is not far from the modern view, which is that an element is any substance which consists of atoms all of the same kind. Ninety-two such substances exist in Nature and certain others have been made in the laboratory in recent years.

The term "substance," it should be noted, includes solids, liquids and gases, for matter exists in all of these forms and which of the three shapes it takes at any moment is only a matter of temperature. Cavendish, Dalton,* Lavoisier† and other early chemists had no doubt some realisation of this. They knew that metals could be melted into liquids by heat and that mercury solidifies if its temperature is sufficiently reduced. To-day liquid air is no longer a marvel and the Sparklet bulb, containing solid carbonic acid gas, is an article of commerce.

A compound was to the early chemists, and is to the chemists and physicists of our day, a substance whose ultimate small particles consist of close associations of the most minute pieces into which elements can be divided. The smallest parts of a compound are now called molecules, each of which consists of two or more atoms of elements tightly bound together. Thus the molecule of the compound water is a coalescence into one tiny body of two atoms of hydrogen gas and one atom of oxygen gas. The chemist's shorthand symbol for the atom of hydrogen is H, and that for the atom of oxygen O; hence he writes for the molecule of water: H_2O —the close combination of two hydrogen atoms with one of oxygen. By means of such symbols the numbers of the atoms of all the elements which constitute a molecule of any compound can be indicated. When in a lighter moment a chemist bursts into such a ruthless rhyme as:

* 1766-1844.

† 1743-94.

*Young Willie was a thirsty soul,
But now he is no more;
For what he drank for H_2O
Was H_2SO_4 .*

He means simply that the liquid which Willie drank consisted not of water molecules made up of two atoms of hydrogen and one of oxygen, but of something in which two hydrogen atoms are combined with one of sulphur and four of oxygen.

This compound, though made up of the individually harmless elements hydrogen, sulphur and oxygen, strongly attacks many metals and would certainly prove lethal to any human being who drank a quantity of it, for it is sulphuric acid. Strictly speaking it is incorrect to speak of a quantity of sulphuric acid as H_2SO_4 , for the symbol refers only to one molecule of the liquid. It is not, however, unusual, wrong though it may be, to use the chemical shorthand symbols to designate either an element or a compound in bulk.

Matter may also take a third form. Iron, copper, carbon, oxygen and uranium are *elements*, each built up of atoms of one particular kind. Water, sulphuric acid, petrol, sugar and common salt are *compounds*: each of these substances consists of an assembly of similar molecules, all built up from the atoms of elements. The smallest particle of any is a molecule of the same kind as all the other molecules composing the substance. But there are also *mixtures*, of which the air that we breathe is an example familiar to everyone. There is no such thing as a molecule of air: it consists of the molecules or the atoms of a variety of gases, mingled together in surprisingly constant proportions, but not bound up into the molecules of a compound. The gases which go to make up air are readily separable from one another; our lungs, in fact, perform one such

separation at every breath we take by enabling the red corpuscles of the blood to extract oxygen from the mixture of gases which we inhale many times a minute during the whole of our lives.

Air, actually, is a mixture of approximately one part of oxygen with four of another elemental gas, nitrogen (symbol N). It also contains small proportions of the rare gases helium (He), neon (Ne), Argon (A), Krypton (Kr) and Xenon (Xe), as well as water vapour (H_2O) and carbonic acid gas. The last, as its symbol, CO_2 , shows, is a compound in which all molecules consist of one atom of carbon combined with two of oxygen.

The balance of the atmosphere is preserved all over the world by the different needs of animals and plants. Animals, by means of their lungs or other kinds of breathing apparatus, extract oxygen from the air and supply carbonic acid gas to it. The same is true of the fires and the furnaces which man finds necessary to his existence: animal life and combustion are similar processes, for each consists in making atoms of oxygen from the atmosphere combine with carbon to form carbonic acid gas: we burn up the carbons which form a large part of our food just as a furnace burns other forms of carbon, such as coal, anthracite or coke.

Plants, on the other hand, breathe in carbonic acid gas by day, using it to build the carbon compounds which will later form food or fuel for us. At night plants do breathe in some oxygen (that is why hospital nurses are so insistent on removing flowers at bedtime); but their demands are not great and at that time the majority of animals are quiescent and so convert comparatively little oxygen into carbonic acid gas.

Animals do not require nitrogen for their well being. It serves merely to dilute the air that they breathe. If they inhaled "neat" oxygen, the burning-up process of life

would be unduly accelerated; they would mature, age and die much too quickly. Combustion in them would be too rapid; they would turn oxygen and carbon into carbonic acid gas too rapidly, just as a stove does when in a moment of absent-mindedness it is left with dampers and draught fully open. Plants, on the other hand, need a great deal of nitrogen. Some of them, such as peas, vetches and beans, have their own special methods of extracting it directly from the air. Others rely on the aid of bacteria which cause animal and vegetable products to rot down into humus or compost by abstracting nitrogen from the air and causing it to combine with them.

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CHAPTER III

Clue follows Clue

IN ALL OF THE PROCESSES that we have discussed, as well as in countless others, the change of matter from one form to another is continually taking place, either by the conversion of two or more elements into a compound, or by the combination of two or more compounds and the rearrangement of the atoms concerned into fresh compounds. Two atoms, for example, of the oxygen inhaled by the lungs combine with one atom of carbon removed from some part of the body by the blood to form a molecule of exhaled CO_2 , or carbonic acid gas. These rearrangements involve no alterations in the number, the kind or the weight of the atoms concerned. If, for instance, two million* hydrogen atoms and one million oxygen atoms are made by explosion to change from a mixture of gases into a compound we find always that—

(1) the resulting water vapour contains the original three million atoms, no more and no less;

(2) the new molecules consist of combinations of oxygen and hydrogen atoms: the individual atoms have, so to speak, lost their identity by combining closely to form fresh molecules, but they are all still there;

(3) the water vapour produced has the same total weight as the original oxygen *plus* the original hydrogen.

When a cigarette is smoked combustion—the rapid conversion of one kind of matter into another—has no effect whatever on the number, the kind or the weight of

* Actual numbers are far greater. The amount of water formed by 2,000,000 atoms of hydrogen and 1,000,000 would be almost infinitesimal.

the atoms concerned. Could they be collected without loss or addition, the ash, the smoke and the stub, less the oxygen obtained from the air in the process of burning, would weigh exactly as much as the original cigarette, and would contain precisely the same numbers and kinds of atoms. All that has happened is that additional atoms of oxygen from the air have combined with the original atoms to bring about rearrangements of the atoms and the molecules of the compounds of which tobacco and paper are built up; the original matter has been reshaped into smoke, ash and so on. Nothing is either gained or lost: there is as much matter as there was before, but it has been transformed into new kinds of matter.

This is the principle of the *conservation of matter*.

Another important clue was discovered by John Dalton, who saw that the discoveries of his time led at once back and forwards. They led back because they indicated that Democritus had been right in regarding matter as composed of tiny indivisible bodies and forwards because they showed how to obtain some information about the nature of these atoms. Dalton formed these conclusions after finding that when two elements went into combination to form a compound, this compound was always built up of the same proportion by weight of the elements concerned. The oxygen part of water was invariably eight times as heavy as the hydrogen part, but since the oxygen part of each water molecule consisted of only one atom, whilst the hydrogen part consisted of two atoms, a very simple calculation (on the lines of: If a herring and a half cost three-ha'pence, what would one herring cost?) of the relative weights of each of these elements could be made:

If one oxygen atom weighs eight times as much as two hydrogen atoms,

Then one oxygen atom weighs sixteen times as much as one hydrogen atom.

Hence, if we call the weight per atom or *atomic weight* of hydrogen 1, the atomic weight of oxygen must be 16.

Avogadro* was convinced by his experiments that pure oxygen, and pure hydrogen were made up of molecules, each of which consisted of two atoms bound together. In the "free" state, when neither gas was combined with another element, you had always H_2 or O_2 , but never simply H or O. In forming compounds these molecules could become split into their component atoms. Following up this line of investigation, he was inspired to make one of the most remarkable guesses in the history of science; he suggested that in a given volume—say, a pint—of *any* gas there must be always an equal number of molecules, provided that the temperature and the pressure were the same.

Now since the atomic weight of oxygen is 16 and the molecule consists of two atoms, the *molecular weight* of the oxygen molecule must be twice 16, or 32 and that of hydrogen twice 1, or 2. On the basis of Avogadro's theory the conclusion was reached that a volume of 22.4 litres (about 5 gallons) of *any* gas at a certain temperature and pressure must always weigh exactly the same number of grams (a gram is roughly one-thirtieth of an ounce) as the molecular weight of the gas. In other words, 22.4 litres of oxygen must weigh 32 grams; the same volume of hydrogen, 2 grams and so on. From this it follows that this same number of atoms must be contained in as many grams of a gas as the figure of its atomic weight. Thus, the atomic weight of oxygen being 16, sixteen grams of oxygen contain the Avogadro number of atoms. Avogadro's original hypothesis has been proved to the hilt by all subsequent

* 1776–1856.

investigations and experiments. His number, originally 602,000,000,000,000,000,000,000 or 602,000 trillion has been calculated, re-calculated, checked and re-checked. The latest figure is very little different from that first found: it is 602,340,000,000,000,000,000,000.

Such enormous numbers are very inconvenient to write or to print in this "longhand" form. We can write 100 as 10^2 , the small 2 signifying that two tens are multiplied together; similarly 1,000 becomes in "shorthand" 10^3 ($10 \times 10 \times 10$), 1,000,000 becomes 10^6 and 602,000 trillion boils down into the much handier form 602×10^{21} , or the still more concise 6.02×10^{23} . You will see that the small 2 or 6 or 21 indicate the number of noughts following the whole number. The meaning of the 23 in 6.02×10^{23} is that to write the number in full we must move the decimal point 23 places to the right. We move it two places by writing 602 and the movement is completed by adding 21 noughts. The latest figure for the Avogadro number is 6.0234×10^{23} atoms in the number of grams equal to the atomic weight of an element.

Figures of this stupendous size are utterly beyond the comprehension of the ordinary human mind and it is difficult to obtain even an idea of what they mean. The population of the world is about 2,000,000,000 or 2×10^9 human beings. In our shorthand it is easy to divide one huge number into another. We can find out how many atoms in about $\frac{1}{2}$ oz. (16 grams) of oxygen would go to each man, woman and child (could they be equally shared out) by dividing 2×10^9 into 6.02×10^{23} . To do this *divide* the 6.02 by the 2 and subtract the 9 from the 23; the answer is 3.01×10^{14} : there would be 301 billion atoms in that $\frac{1}{2}$ oz. for every living soul!

Suppose that every one of the stars seen as individual points of light on a clear, dark night represented a world with a population equal to that of our own earth. We

know, of course, that this could not actually be the case, for the stars are suns, not worlds. But let us, for all that, imagine each as a world with 2,000 million inhabitants. How far would one half-ounce of oxygen atoms go if they were shared out? First of all how many stars does the unaided eye see as points of light when conditions are most favourable, that is on a clear winter night with no cloud and no moon? If you are reading this on such a night, take a look at the heavens and make your estimate before going further.

Most people, probably, would answer "several millions"; the more cautious might suggest "some hundreds of thousands"; both would be wildly in error: and so, I fancy, is your guess, unless you have already come across this question and its answer elsewhere. In these latitudes the number of stars visible as separate light-points is about three thousand! A further glance at those apparently innumerable glittering points makes you realise that even 3,000 is a very large number for our poor limited minds to appreciate. To see a million stars we should have to scan 300 skies like the one we know!

If all of those 3,000 stars were worlds, each with a population of 2,000,000,000, the total number of men, women and children awaiting the distribution of the 6.02×10^{23} oxygen atoms would be $2 \times 10^9 \times 3 \times 10^3$, or 6×10^{12} (*multiply* the 2 by the 3 and *add* the small 9 and the small 3). Dividing this into 6.02×10^{23} , we have in round figures 10^{11} , or 100,000,000,000—one hundred thousand million.

You will see, then how difficult it is to form any clear mental picture of the vast number of atoms which go to make up even so small a quantity of matter as $\frac{1}{2}$ oz. of oxygen. A gas is a gas simply because in that state the atoms are very loosely packed: there are big empty spaces between each atom and its nearest neighbours. The 16

grams of oxygen of which we have been thinking would be a large bucketful. A similar big bucket filled with water would weigh about 25 lb. Fill the same bucket with solid lead and you could not lift it.

The weight or *mass* of a bucketful of matter depends upon two things: (1) the state of the particular matter with which the bucket is filled and (2) the nature of that matter. If the matter is in the gaseous state (steam) its atoms are widely separated and the total mass is comparatively small; in the liquid or the solid state (water or ice) the individual atoms are much more tightly packed and the weight is greater. The heaviest bucketful consists of a solid composed of tightly packed atoms, each with an individual mass large in comparison with those of, say, hydrogen or oxygen. The lead atom weighs roughly 207 times as much as that of hydrogen. The atoms of solid lead are much more closely packed than those of hydrogen gas. A small child would have no difficulty in lifting a bucket filled with hydrogen gas, but a very strong man would be defeated by a bucket of the same size filled with lead.

Now let us take stock of the progress of the inquiry into the nature of matter up to the point reached rather more than a century ago. As we shall see, some of the conclusions were correct; some were partly correct; some were wrong.

(1) It was established that matter of all kinds consisted of atoms.

(2) These atoms were believed to be small solid bodies.

(3) Each element was believed to consist of atoms all of one particular kind.

(4) Hydrogen atoms were the lightest of all. The atomic weights of other elements were believed to be exact multiples of that of hydrogen.

(5) All the atoms of any one element were believed to be identical as regards size and weight.

(6) From (3), (4) and (5) it was rather rashly concluded that the nature of any atom was determined solely by its weight. If an atom was sixteen times as heavy as a hydrogen atom, it *must* be an atom of oxygen; if fourteen times as heavy, it *must* be one of nitrogen; if fifty-six times as heavy, it *must* be one of iron.

(7) Science, therefore, if it didn't then know all the answers, believed that at any rate it knew how to obtain them. All that had to be done was to determine the atomic weights of all the known elements and to make a table of them. There would be gaps representing the then unknown elements. But the atomic weights of the elements still to be discovered could be inferred from the table and the figures thus obtained would assist the tracking down of elements not yet identified.

It all seemed too easy! Actually, it was far otherwise. Again and again, when the detectives of science have seemed to be on the verge of providing the final answer to the question, "What is matter?" some fresh and quite unexpected development has occurred to prove either that they were following a false scent or that they did not fully understand the implication of the clues that they then possessed. Sometimes, again, the measuring instruments available at the time have turned out later not to be sufficiently accurate to justify the conclusions reached with their help. It is as if Sherlock Holmes, finding by means of his pocket foot-rule that the footprint in the flower bed below the library window and the bootsole of the Man with the Crooked Thumb each measured 12 inches, had intimated to Inspector Lestrade that an arrest might be made. Subsequently, however, it was shown in court that measurements with a micrometer of the latest type

proved conclusively that the 11.925-inch footprint could not possibly have been made by the 12.015-inch soles worn by the accused.

William Prout* made a brilliant suggestion in the year of Waterloo. Basing his arguments on what then appeared to be an established fact—that the atomic weights of all elements were exact multiples of that of hydrogen—he put forward the theory that all matter consisted ultimately of hydrogen atoms. In his view a close combination of sixteen hydrogen atoms could in some way become an oxygen atom; a combination of thirty-two hydrogen atoms could become a sulphur atom and so on. So convinced was he of the correctness of his theory that he invented the name “protyle,” or basic material (from the two Greek words meaning “first” and “matter”), for the hydrogen atom.

Prout's theory had few supporters at the time, though we know nowadays that he was very nearly right. Shortly after he had advanced it, his theory was completely discredited owing to the discovery of a new and very puzzling clue. Newer and better measuring instruments and measuring methods showed that hardly any known element had in truth an atomic weight which was an exact multiple of that of hydrogen. Nor could any known element be found with an atomic weight such that those of all elements of lighter weight could be divided into it exactly, whilst those of heavier elements were all exact multiples of it. Whatever element was taken as having “standard” atomic weight, the relationship which the weights of the atoms of the others bore to it could be expressed only by a whole number and a fraction or some decimal figures.

Still, atomic weights appeared to offer the best basis for identifying and classifying the elements and, if Nature

* 1785–1850.

refused to deal in whole numbers, the best must be made of a bad job. We know now that Nature *does* deal in whole numbers, though this could not possibly have been ascertained in those days in the light of the facts and in view of the apparatus then available.

Since Nature appeared to have provided no convenient standard atom to the weight of which those of all the other elements might be referred, science decided to take a line of its own. The atom most commonly found in the combinations of atoms which form compounds was agreed to be oxygen. If the atomic weight of oxygen were taken as exactly 16, a table could be constructed in which all known elements could be shown in the order of their atomic weights from the lightest to the heaviest. Further, each of the atomic weights based on Oxygen=16 could be expressed with quite adequate accuracy by means of a whole number followed by not more than two decimal figures.

The protyle theory put forward by Prout appeared to be definitely exploded: if no other atom had a weight which was an exact multiple of that of the hydrogen atom, it seemed to be clear enough that the heavier atoms could not possibly be conglomerations of hydrogen atoms. Therefore the hydrogen atom could not be the basic material of the universe. Nevertheless, the way leading to the complete knowledge of the nature of all matter still appeared to be clear of every obstacle. Accept as fact No. 1 that the atom is a minute solid body, probably globe-shaped; accept as fact No. 2 that the weight-per-atom, or atomic weight, is the sole difference between one element and another; don't bother your head about the unquestionable fact that, whatever standard of reference be taken, only one or two elements have atomic weights that are whole numbers; find the atomic weight of all known elements; discover the remaining elements and

ascertain their atomic weights; everything will then be known about matter; the detectives of science will have evolved a complete solution of the problem. These things, it seemed, should not take very long to accomplish. The goal was almost certainly within sight.

“Almost?” Well, not, as it proved, quite. “Certainly?” Events were to show before long that the complacent attitude maintained by science up to near the close of the Victorian era was to receive not one but many shakings; shakings severe enough to force the realisation that the unravelling of the great mystery was still a long, long way off.

CHAPTER IV

Fresh Trails

THE FIRST SHAKE-UP was so severe that it produced something like the effects of an earthquake. It came from the discovery of a particle of matter far lighter than the hydrogen atom. This was the electron, first definitely identified in 1897 by Sir J. J. Thomson.* Before this date other workers, such as Sir William Crookes† and Sir Oliver Lodge‡ had given much attention to the problems presented by the passage of an electric current through a vacuum, through gases and through solutions of metallic salts. Crookes found that in the tube which bears his name an electric current could be made to pass through a vacuum. To this stream of current he gave the name “cathode rays,” because the flow emanated from the cathode, or negative electrode, of the tube and because the current could be made to form something like a beam by causing it to pass through a narrow slit. Later investigations convinced him that the “rays” consisted of matter in an entirely new form. Crookes described them as displaying matter not in the solid liquid or gaseous state, but in a new state—the radiant. His great work paved the way for the enormously important advances made by Thomson.

Thomson was sure that the cathode rays consisted of minute particles of matter. His task was to discover, if possible, the nature of the particles and their individual weight. For some years science had been trying to evolve new techniques to enable it to find out more and more about particles so small that there was no hope of seeing

* 1856-1940.

† 1832-1919.

‡ 1851-1940.

them, even with the most powerful microscope. If a thing is too small to be seen by itself, much may be learnt by setting it in rapid motion and by noticing the effects which it produces on colliding with other things.

Imagine the earth visited by a gigantic inhabitant of some other planet whose eyesight is such that an object as small as a rifle bullet is invisible to him. Watching battles in progress amongst human beings, he would notice that they were able to bowl one another over at quite considerable distances. He might, therefore, deduce that the midget creatures whose strange antics he was observing possessed a means of propelling little particles of matter at each other with considerable velocity. Later, he captures some soldiers, complete with rifles and ammunition. By making them shoot at an iron plate at a fixed distance he can determine with the help of an accurate timing device the average velocity of the projectiles. Next he installs at the target apparatus which measures the force of the blow administered by each bullet as it strikes the plate. He now knows the amount of energy conveyed by the bullet and approximately the velocity with which it is travelling when the collision with the plate occurs. Armed with these facts, he can calculate the weight or mass of the to him invisible bullet.

There are other ways in which he could make the calculation. One would be to get one of his captives who was a first-rate shot to aim at a bull's-eye whilst a strong wind was blowing straight across the range and to measure the distance which the bullet was blown aside, or deflected, by the wind. The heavier the bullet and the greater its speed, the less would it be deflected by a wind of known strength blowing at right angles to its path.

In his investigations Thomson used an improved version of the Crookes tube. Means were found of focusing the rays into a much narrower beam, with the result that the

glowing patch on the screen was reduced to a spot of light. The next discovery was that if two plates were put into the tube as shown in Fig. IV.1, the beam could be deflected and the spot made to travel over the screen by charging the plates electrically. The beam is always deflected towards whichever plate is positively charged and away from a negatively charged plate; and the greater the electric charges on the plates, the greater is the deflection of the beam.

It had long been known that like charges of electricity

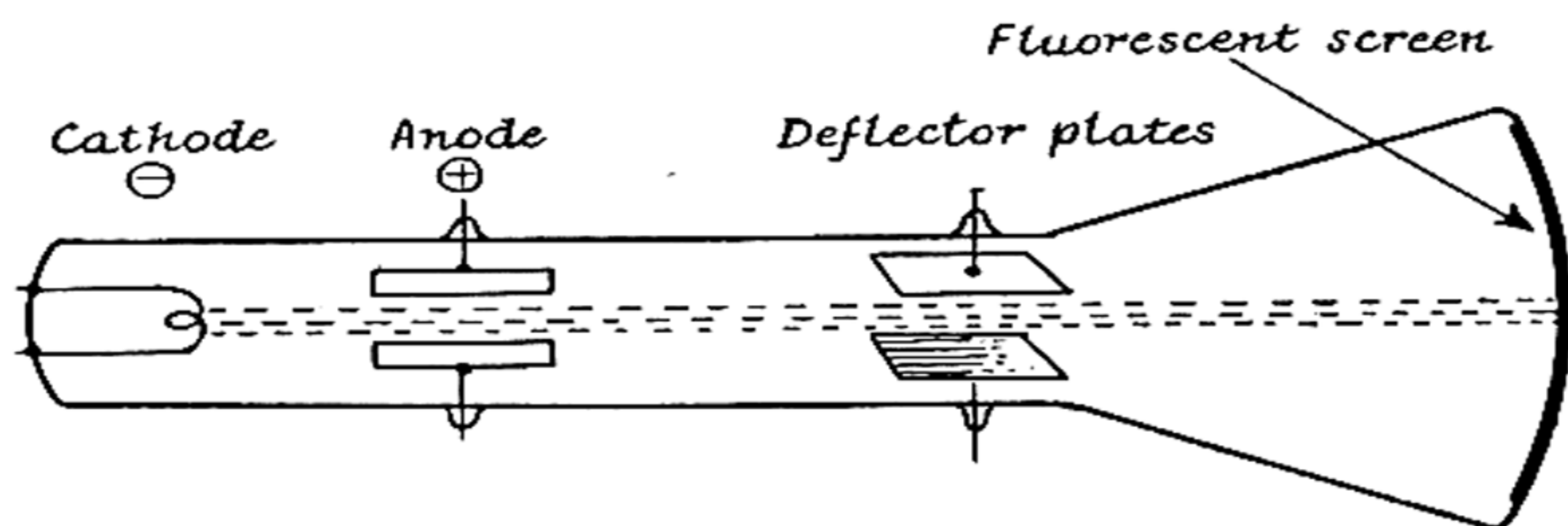


FIG. IV.1. An early simple type of cathode-ray tube with one pair of deflector plates.

repel one another and that unlike charges exercise mutual attraction. The beam was known to be electrical in nature, and since it was repelled by the negative plate and attracted by the positive it was rightly inferred that it must consist of a stream of minute particles of negative electricity. What did each of them weigh? How big were they? What was the amount of the electric charge on each of them? These were the questions that Thomson set himself to answer.

The apparatus seen in Fig. IV.1 was named the cathode ray tube. If a second pair of deflector plates is installed in it at right angles to the first, they allow the beam to be deflected horizontally as well as vertically. In fact, by applying suitable charges to the two pairs of plates the spot of light can be made to move to any part of the screen.

Once purely a laboratory instrument, the cathode ray tube, or C.R.T., is rapidly becoming a familiar piece of ordinary domestic equipment, for it is on the screen of a C.R.T. that a television receiver displays its pictures. These pictures are "painted" by the rapid movements of a single tiny spot of light over the screen.

There is another way in which electrons can be deflected. If a thin wire carrying an electric current is placed between the poles of a magnet as in Fig. IV.2, it tends to move out of the magnetic field in the direction

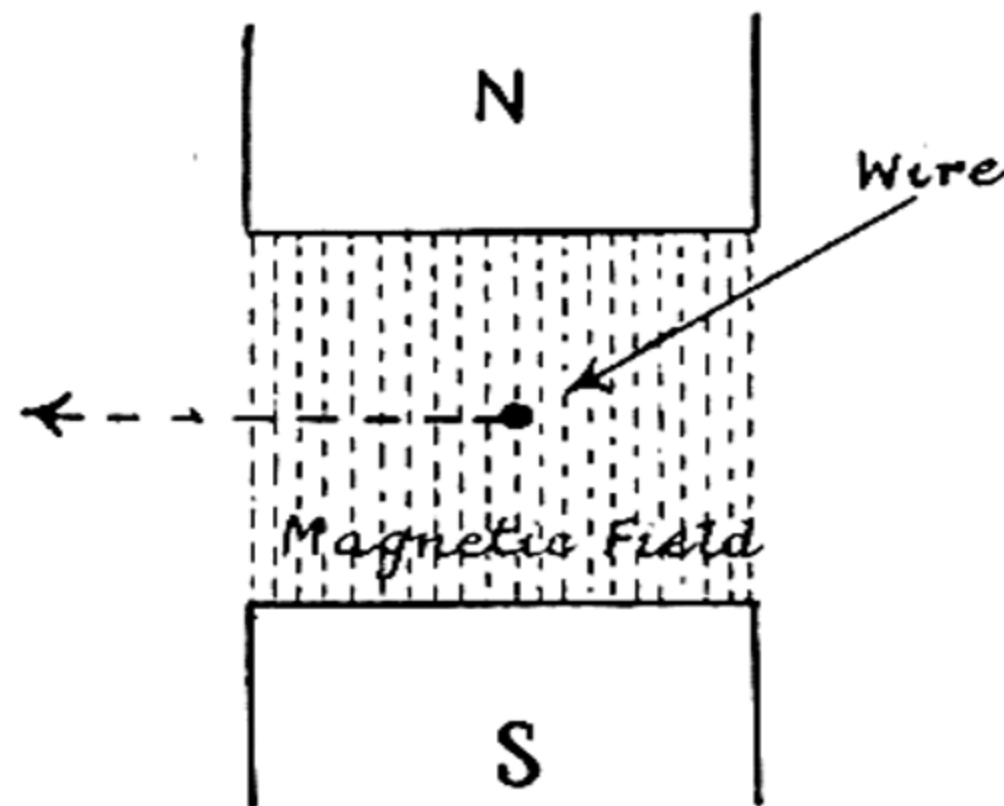


FIG. IV.2. The dot represents a wire which passes through the magnetic field and is free to move. If an electron current is imagined to be flowing away from the eye through the page, the wire will tend to move in the direction shown by the broken line and the arrow. Reverse either the direction of the current or the polarity of the magnets and the wire moves in the opposite direction. A beam of electrons is deflected in precisely the same way by a magnetic field.

indicated by the arrow. Reverse the north and south magnet poles and the movement is in the opposite direction. Now, a current through a wire is caused by a stream of electrons. Imagine the wire as a pipe and the electrons as a stream of water flowing through it—we shall see in a later chapter how the flow of current actually takes place. From the nozzle of a hose a jet of water can be sent through the air without needing the walls of a pipe to hold it together. Similarly, the electron beam through the vacuum of the C.R.T. is a jet of electric current needing no

guiding wire. Pass the electron beam through a magnetic field at right angles to its direction of flow and the deflection seen in Fig. IV.2 occurs: the stronger the magnetic field, the greater the deflection; reverse the magnetic field and the deflection is in the opposite direction. The spot of a C.R.T. can be made to move from side to side or upwards and downwards over a C.R.T. screen by using deflector magnets instead of deflector plates. Magnetic deflection is used nowadays in the vast majority of television receivers.

In the course of his inquiry into the electron Thomson made use of the "mixed" type of C.R.T. shown in Fig. IV.3. This had one pair of deflector plates and one pair

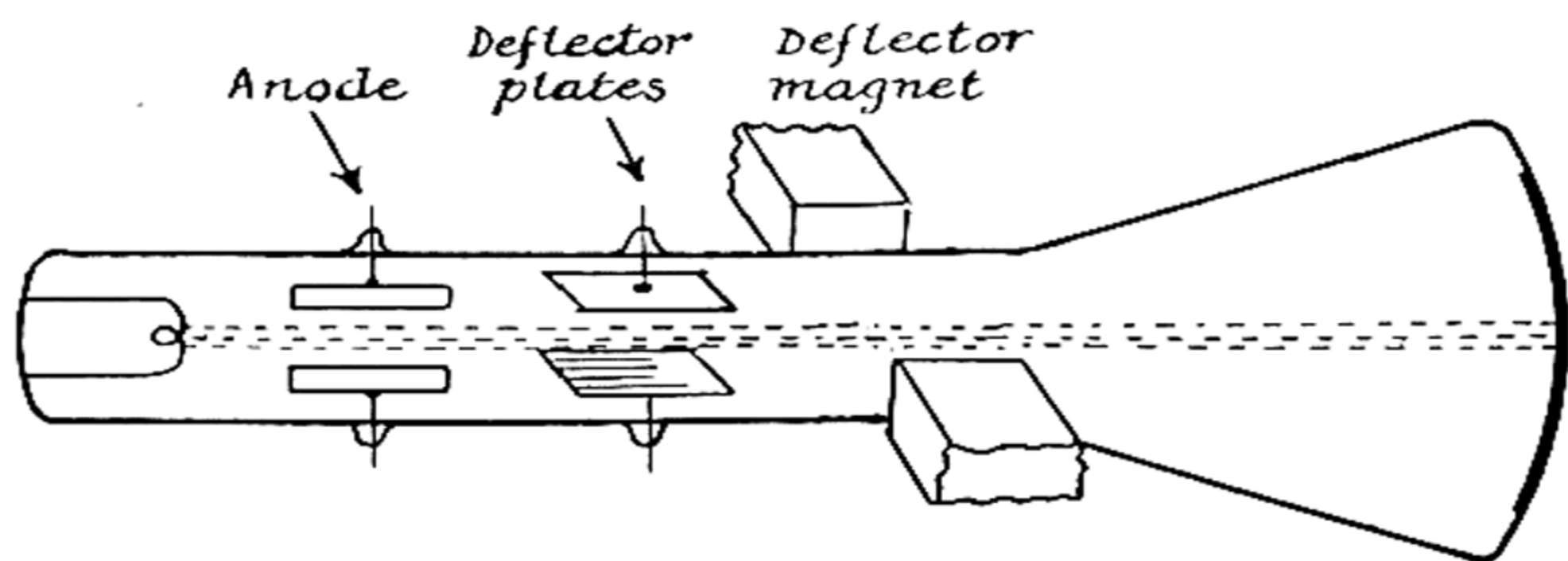


FIG. IV.3. The kind of cathode-ray tube used by Thomson in his investigations. In this the electron beam can be deflected at will by either the electric field of the plates or the magnetic field. Or both electrostatic and magnetic deflection may be applied simultaneously.

of deflector magnet poles. The latter, by the way, were placed outside the tube, for its glass walls have no effect whatever on the magnetic field. Electro-magnets were used since the field could be strengthened or weakened by increasing or reducing the current through their windings; it could be eliminated altogether by switching off the current.

The position of the spot on the screen was first of all marked with no charge on the plates and no current passing through the magnet windings. Next, the spot was moved, say, upwards by applying charges to the plates

and so producing an electric field between them. With the electric field unaltered, the magnet poles were now brought into action. The flow of current through their windings was so arranged that the deflecting influence of the magnetic field between the poles was exactly opposite to that of the electric field between the plates. Weak at first, the magnetic field was gradually made stronger, until it just counterbalanced the electric field and the spot was drawn back to its original position at the centre of the screen. From the relative intensity of the two fields the speed at which electrons moved through the tube could be calculated. A long further series of experiments was necessary before two other important questions could be answered: How much does an electron weigh? (or as scientists put it, What is the mass of an electron?) and: What is its electric charge?

Like the bullets in the experiments of our imaginary giant, electrons were shot through the "cross winds" of deflecting fields and at targets consisting of the atoms or molecules of gases. After an immense number of painstaking experiments, in which the effects of deflecting fields on fast moving electrons and those of the collisions of electrons with other minute bodies were observed and recorded, these two questions were answered. The conclusions reached were something like this:

- (1) The electron is a minute piece of matter.
- (2) It is the lightest piece of matter known, weighing as it does only $1/1840$ as much as the hydrogen atom.
- (3) Electrically, it is negatively charged.
- (4) Each electron has the same negative charge.
- (5) This charge is the smallest that can exist. It is, therefore, the unit of negative electrical charge.
- (6) Besides being a tiny piece of matter, the electron is also a tiny piece of negative electricity.

(7) Since the electron is both a particle of matter and a particle of one kind of electricity, it seems possible that all kinds of matter are nothing more or less than conglomerations of minute particles of electricity.

Whilst these upheavals were taking place in the placid and complacent world of the Victorian scientists two other scientific advances, each profoundly affecting the inquiry into the nature of matter, were made known to an astonished world. The first was the discovery of X-rays by the German physicist, Röntgen.* Had you asked an eminent scientist a year or two earlier to tell you something about transparency, he would most likely have replied that certain kinds of matter, such as glass, celluloid, ice or mica were so constituted that the electro-magnetic waves of light could pass through them; others, on the contrary, were by nature opaque—as, for example, metals, wood, stone and flesh. Opaque substances, he might have continued, are so constituted that they completely bar the passage of electro-magnetic waves: it is, therefore, absolutely impossible to see through them. . . .

You may imagine what a commotion there was when Röntgen, in his early demonstrations, let people see the bones of their own hands, metal objects sealed up in light-tight wooden boxes and so on. It became necessary to revise entirely a whole series of long-standing beliefs which were thought to be established truths. The old ideas of transparency and opacity *were* truths in the light of current knowledge about matter and about electro-magnetic waves. No known electro-magnetic waves could penetrate the opaque substances. Until Röntgen announced his great discovery, it appeared that the shortest electro-magnetic wavelengths that could occur were those producing visible light, or those responsible for

* 1845-1923.

ultra-violet light, which could affect a photographic plate, though they were just beyond the limit of sensitiveness of the eye. And here was Röntgen showing beyond any doubt that rays of far shorter wavelength than the ultra-violet existed and that to them many "opaque" substances were completely transparent.

The human eye could not see directly the images conveyed by X-rays; but these rays could be made to throw a visible image on to a screen coated with certain types of fluorescent material, or they could be used to record on a photographic plate an image which, after the processes of development and fixing, was clearly visible to the eye.

From all this the following new facts were realised:

(1) Transparency and opacity are purely relative terms.

(2) The eye can see through what we call transparent substances simply because waves of the length which produces visible light are able to pass through such substances and to provoke a response from the retina of the eye.

(3) Some substances, such as bone, were almost opaque to X-rays of the shortest wavelength then known; others, including metals, appeared to be completely opaque to them. Were there still shorter rays to which all such kinds of matter would prove transparent?

The second development led almost to the effects of a bomb-shell in the consternation which it caused in the scientific circles of the 'nineties. This was the discovery by Professor and Madame Curie in France of radio-activity. Ever since the days when natural philosophers, as reputable scientists were then called, laughed the alchemists out of court and took over the inquiry into the nature of matter it had been held that one of the basic and indisputable facts, upon which all investigations must be founded, was that

the elements were stable and indestructible things, which could not change their nature. A number of atoms of chlorine could combine with atoms of sodium to form sodium chloride, or common salt; but all the original sodium and chlorine atoms were present in the compound. The chlorine atoms had gone, so to speak, into partnership with those of sodium; but it was possible to dissolve the partnership by the methods of analysis and when this had been done every sodium atom and every chlorine atom concerned was found to be present, completely unchanged in nature, in size, in weight, or in any other way. The atoms of an element, in fact, were minute bodies which could undergo neither change nor destruction, no matter how you treated them. . . .

And now come the Curies giving proofs, which could not be doubted, that the atom of radium was guilty of behaviour which broke all the known rules. Without any provocation, it spent its time in flinging away tiny bits of itself. Nothing was needed to start the process; nothing could speed it up, slow it down or stop it. Every radium atom was fated, sooner or later, to change its nature by behaving in this way. Since the radium atom threw away pieces of itself it must become lighter and lighter. As it was then believed that the nature of an atom—that is, the kind of element to which it belonged—depended entirely upon its weight, it was plain that these continual discards of portions of itself must cause the radium atom to change spontaneously into some other kind of element with lighter atoms. Investigations showed that radium, with an atomic weight of 226.05 (that of the oxygen atom being taken as 16) broke down eventually into the dull and prosaic metal lead, whose atomic weight is 207.21.

But what were the pieces of itself that radium flung away in order to bring about this startling change? It was a change, you will see, just the opposite of that for which

the alchemists had been working. They hoped to transmute one of the cheapest and commonest of elements into the most valuable that they knew. To turn lead into gold was their object. But here was something much rarer and more costly than gold turning itself into lead. The Curies found that in the course of its change from one element into another radium made discharges of three quite different kinds. The exact nature of these was not at first understood and they were all termed rays, being known as alpha, beta and gamma rays (α , β , γ , the first three letters of the Greek alphabet).

Later, as we shall see, it was discovered that the beta rays, like the cathode rays of the Crookes tube, consisted of electrons; that the gamma rays were electro-magnetic waves akin to X-rays, but shorter in wavelength and more penetrating; that the alpha rays were particles of matter, each nearly 8,000 times as heavy as an electron, which carried positive charges. All this, and much more besides, was due mainly to the genius of the greatest investigator who has ever lived: Rutherford.*

Since the alpha particle weighed about four times as much as a hydrogen atom, and since the elements were then believed to be distinguished from one another solely by the weights of their individual atoms, it was concluded that these particles must be helium atoms. But they were positively charged, each having a charge equal but opposite to those of two electrons.

In its normal state an atom carries no charge at all: it is electrically neutral. It was found, though, that atoms could be made to acquire an electric charge under certain conditions. If, for instance, an electric current is passed through a gas the atoms of which were previously in a stable, or electrically neutral condition, an extraordinary change takes place. At any instant some of the atoms

* 1871-1937.

become positively charged, whilst an equal number become negatively charged.

To be able to undergo such changes, atoms could not be simple solid bodies of minute size. Add an electron—the unit of negative electrical charge—to a neutral atom and it will become negatively charged; but how can such an atom acquire a positive charge?

Rutherford saw the atom as something like a miniature solar system. At the centre was a heavy, positively charged body, the nucleus, in which almost the entire weight of the atom was concentrated. Round the nucleus a number of electrons revolved in orbits like those of the planets round the sun. The number of these orbiting electrons varied from element to element; in the normal, or balanced state of the atom, it was always equal to the number of positive charges on the nucleus. Thus each positive charge on the nucleus was exactly cancelled out by the negative charge of an orbiting electron with the result that the atom had normally no electric charge: it was balanced and neutral.

His view of the nucleus itself was that it consisted of a very close combination of particles of positive electricity and electrons. The simplest of all atoms, that of hydrogen, consisted (Fig. IV.4(a)) of one positively charged particle, or proton, weighing 1840 times as much as the electron: the atom next in simplicity, that of helium, had an atomic weight of 4 and was found to have two orbiting electrons. Hence its make-up appeared to be that seen in Fig. IV.4 (b). The nucleus was held to contain four protons and two electrons and round it two further electrons revolved. What we may call the “electrical sum” of the neutral helium atom was:

In the nucleus:

$$4 \text{ protons} = +4$$

$$2 \text{ electrons} = -2$$

$$\text{Total nuclear charge} \quad . \quad . \quad . \quad . \quad . \quad +2$$

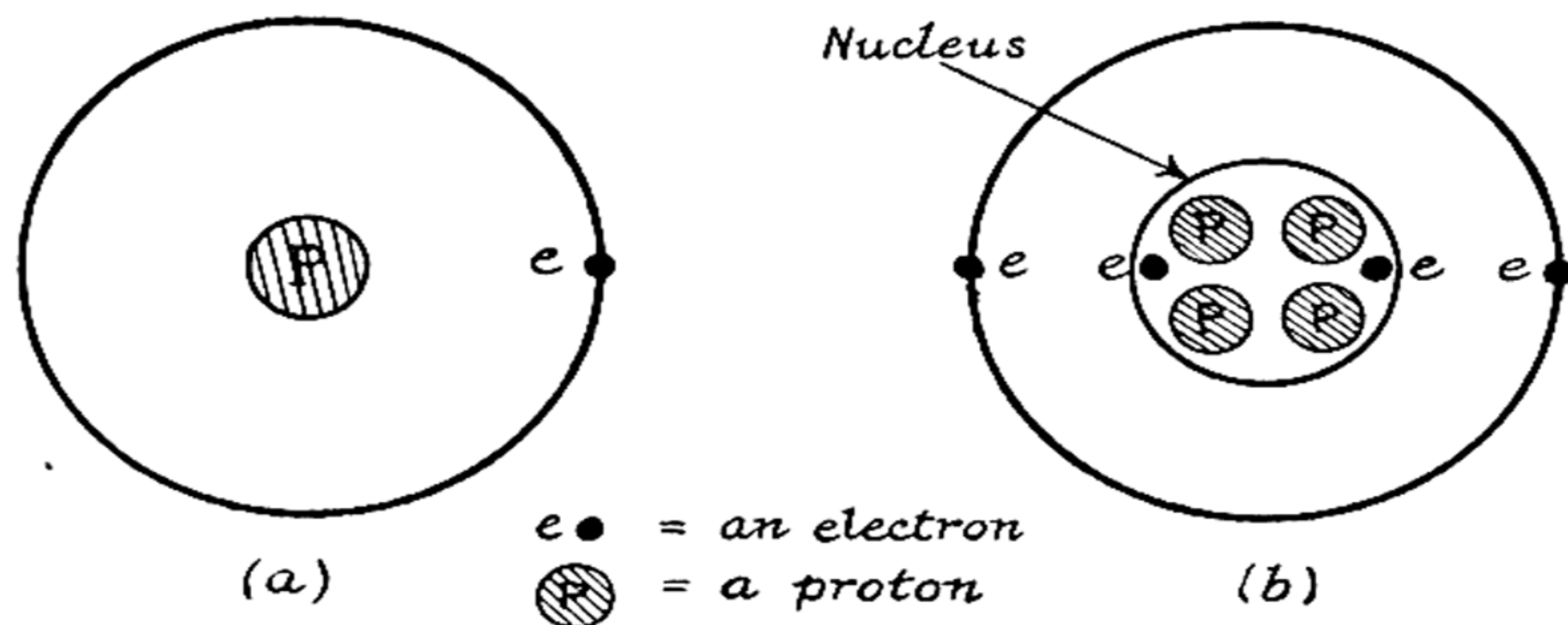


FIG IV.4. (a) Rutherford's conception of the make-up of the hydrogen atom; (b) how he imagined the helium atom to be constituted. The modern view of the hydrogen atom is similar; but it is not now believed that electrons are components of the nuclei of other elements.

In the orbits

2 electrons = -2

Total charge in orbits -2

Total charge of atom $+2 - 2 =$ 0

Rutherford was not satisfied with his picture of the constitution of the nucleus. He believed that it would be changed by future discoveries; as, indeed, it has been. But his general conception of the atom has been shown to be correct by all subsequent discoveries: all atoms consist of a positively charged nucleus, surrounded by a kind of shell of rapidly revolving electrons. An atom can acquire a negative charge of one unit by capturing temporarily an additional orbiting electron. In this state the negative charges outnumber the positive charges by one and the electrical sum of the atom is -1 . It may also become positively charged to the extent of one or more units by the temporary loss of one or more orbiting electrons, in which case the positive charges of the protons in the nucleus are greater than all the negative charges in the atom. If one electron is lost the electrical sum now becomes $+1$.

An atom in which the positive and negative charges exactly balance is said to be neutral; if the positive charges outnumber the negative, it is called a positive ion, from the Greek *ion*, meaning "travelling thing." Similarly, the atom with a preponderance of negative over positive charges is a negative ion.

It was now possible to see just what the alpha particles ejected by radium were. Weighing four times as much as hydrogen atoms but having a double positive charge, they could hardly be anything else but the nuclei of helium atoms. Each had lost its orbiting electrons and its electrical sum was $+4-2=+2$, against the $+4-4=0$ of the balanced helium atom. The truth of this conclusion was later verified by collecting a quantity of the alpha particles. What had been collected proved to be a minute amount of the gas helium.

At this point we had better take stock once more and see where the detectives of the physical laboratory had got to in their quest for an answer to the at first sight simple question: What is matter?

They had come to the conclusion (afterwards to be rather rudely upset) that matter of all kinds was built up of only two kinds of bricks: protons and electrons. The mortar binding the bricks together was provided by the enormous attractive forces between particles carrying electric charges of opposite kinds.

They still believed that the nature of any atom was determined by its weight, though some of them had begun to have a feeling that this view might not be entirely correct.

They had rightly decided that every atom consisted of a positively charged central core, or nucleus, surrounded by orbiting electrons, whose number was such that in the balanced state of an atom they exactly cancelled out the positive charges on the nucleus. If the positive nuclear

charge was one electrical unit, there must be one orbiting electron to provide the balancing negative charge. Similarly, if the nucleus had 12, 25 or 92 positive charges they must be offset by the presence of 12, 25 or 92 electrons revolving in orbits round it.

Another correct decision was that, despite its minute size, the atom consisted mainly of empty space. At its centre was the nucleus, containing nearly the whole of the mass, or weight of the atom. Suppose we try to make a scale drawing of an average atom. Represent the nucleus by a dot the size of a pin's head. Now draw a circle some 35 feet in diameter round the central dot and here and there on the circumference of this circle and inside it put in a few small dots, standing for the orbiting electrons. Actually, of course, we ought to surround the central pinhead dot not by a circle, but by a sphere 35 feet in diameter, for the atom, far from being flat, has length, breadth and thickness. Our scale-drawn atom with the nucleus as a dot the size of a pin's head is thus as big as a house. But there is this difference: in a house built of concrete or stone, or of bricks and mortar, the total weight is more or less evenly distributed. The foundations, the walls, the floors and the ceilings are the heaviest parts and the air contained by them as the atmosphere of the various rooms is the lightest. The average weight, however, of the structure is the same throughout.

Very different is the distribution of weights in the atom. Suppose that a house weighs 100 tons; then in our scale model of the atom more than 99.9 tons must be concentrated in the central pinhead dot. Cut off the head of a pin with a pair of wire-cutters. Can you imagine that tiny thing weighing as much as a house? It is difficult to do so, yet it would if the metal of which it is made were in the same concentrated condition as the nucleus of an atom. Matter in a super-dense state does actually exist in some

parts of the universe. Certain stars, known as "white dwarfs," are small in size, but emit intensely bright light because they are far hotter than our sun. "If," wrote Sir J. H. Jeans, "we could pack our terrestrial goods as closely as these stars are packed at their centres, we could carry about 100 tons of tobacco in a tobacco pouch and several tons of coal in each waistcoat pocket."* Jeans explains that at the centres of such stars matter must be in the form of the nuclei of atoms, shorn of their orbiting electrons.

Such, then, was Rutherford's picture of the atom. Remember that he was not completely satisfied with it himself, but believed, rightly, that future discoveries might throw a different light on the composition of the nucleus. So far though, every modern advance in atomic physics had confirmed his conception of the atom as a tiny body, consisting mainly of empty space, with a central nucleus containing nearly the whole of the weight and a number of far lighter electrons whirling round it in distant orbits. The word "distant" is used relatively, for the diameter of the hydrogen atom—that is to say the diameter of the orbit of its single revolving electron—is no more than one hundred-millionth of an inch. But the diameter of this orbit is about a 100,000 times that of the nucleus.

The atom resembles in many ways a model on a minute scale of the solar system. The diameter of the sun is some 800,000 miles. If we enlarge a hydrogen atom to the size of the solar system, the orbit of the single revolving electron is 80,000,000,000 miles in diameter and its average distance from the nucleus is half as many miles. On this scale, in fact, the hydrogen atom is represented by a central sun with a single planet about 400 times as far away from it as the earth is from the sun! In between the sun representing the nucleus and the planet representing

* *The Stars in Their Courses*, Chapter V.

the electron there is just space, empty so far as any kind of matter is concerned, but filled with the intense electric field existing between proton and electron. Like our own universe, the atom consists mainly of the emptiness which we call space. The electric field is represented in our super-large-scale model by the gravitational field between the sun and the distant planet.

A planet such as our own earth is attracted by the enormous gravitational force of the sun; it also attracts the sun. The planet does not fall into the sun because it is moving at high speed. The effect of mutual attraction between a heavy body and a lighter one moving with a high velocity is to cause the latter to revolve round the former in an orbit. The attractive forces between a positively charged nucleus and a negatively charged electron are enormously greater than those of gravity; but the velocity of the electron is much higher than that of a planet with the result that in the atom it also describes an orbit.

Before Rutherford's work was finished the general shape, size and make-up of the atom had been determined and explained fairly satisfactorily. Once again it seemed to many of the detectives in the world's physical laboratories that the end of their quest was in sight. There appeared to be only two fundamental bricks, the proton and the electron, from which every kind of matter was built up. The weights, the sizes and the electric charges of these had been determined. Follow up these clues, which should not need more than a few years' work, and you would have a complete answer to the question: What is matter?

Rutherford was not amongst those who took this view. He suspected that there might be bricks of at least one other kind and that the end of the quest was by no means so nearly in sight as so many believed. He realised that the picture of the atom that he had formed was only a

general picture. The real problem was to discover just how its inmost heavy part, the nucleus, was made up. He accepted the view that the nucleus was composed of a closely-bound system of protons and electrons only as something that was true in the light of the knowledge reached by him and his contemporaries. He expected that the composition of the nucleus would be found eventually to be less simple and his beliefs were later proved to be abundantly right.

Chemists as Detectives

FROM SOON AFTER THE MIDDLE of the nineteenth century discoveries had been made from time to time and theories put forward which caused at any rate temporary shakings of current beliefs about the nature of matter and of the atoms of which it is composed. In the course of their experiments chemists found that most of the known elements could be arranged in certain classes. Some were solids, one (mercury) semi-liquid, some gases. Some were metals, some non-metals. Some produced violent chemical reactions; some, mild reactions; some, no reactions at all. The atoms of some, in forming compounds with atoms of other elements, could provide one bond apiece to link up the combination; others could furnish two, three or four bonds. A few were incapable of providing any bonds at all and so did not form compounds. Then there was the question of atomic weights, which, remember, were still held to be the characteristics that distinguished one element from another. Aluminium was aluminium because it was composed of atoms with a weight, or mass of 26.97 on the basis of a weight of 16 units for the oxygen atom. Similarly, what made sulphur sulphur, or nitrogen nitrogen was that they were composed of atoms weighing 32.06 and 14.008 units respectively.

As Nature usually arranges things in an orderly and tidy manner, it seemed likely that it should be possible to classify the elements in some kind of table, just as the zoologists had succeeded in classifying animals and the botanists plants. A good many methods of classification were suggested and led to heated controversies in the

scientific world. None was quite successful until a Russian scientist, Mendeleev, evolved the Periodic Table. In his table the horizontal classes are called periods and the vertical classes groups. To make his table Mendeleev wrote down the names of all the then known elements in the order of their atomic weights, leaving gaps for those still to be discovered. He then numbered the elements from left to right in his periods.

There could be no doubt that he had evolved a perfect classification. All of the "alkali metals," for example, are in Group I. These are lithium, sodium and potassium, so called because their oxides are dissolved by water to form alkaline solutions. The halogens (iodine, bromine, fluorine and chlorine) fall into Group VII. Their name is of Greek derivation and means literally "creators of salts": the common salt, for instance, with which human beings have seasoned their food from time immemorial is *chloride* of sodium. Later, when the inert gases, neon, argon, xenon, krypton and radon, were discovered, it was found that they all fitted into Group O. As none of them furnishes even a single linking bond they form no compounds and so are inactive, or inert.

All, however, was not quite plain sailing in the composition of the Periodic Table. If you examine it carefully, you will find that not quite all the elements are in what scientists of the days when it was drawn up considered to be the proper order. Though argon with an atomic weight of 39.944 is in the 18th place, it is the 19th element in order of atomic weight. The 19th place is occupied by potassium, the atomic weight of which is only 39.10. Again, cobalt in the 27th place has a higher atomic weight—58.94 against 58.69—than nickel in the 28th place, whilst iodine, with an atomic weight of 126.932, is No. 53 and tellurium, with the higher atomic weight of 127.50, is No. 52. No explanation could be found at the

time. There was no doubt that the atomic weights of these four elements were correct; and equally no doubt that the places assigned to them were the only ones that they could occupy in the table. It seemed that Nature had been a little untidy in her arrangement of the atoms, just as it was accepted that she had been a little untidy in giving them weights which were not whole numbers. In any case her plan of the elements was clearly shown by the Periodic Table, the correctness of which was proved as the years went by and new elements were discovered which fitted exactly into the gaps in the table waiting to receive them. Scientists in general were not particularly perturbed about these seeming discrepancies. They accepted them as proof that Nature has certain exceptions to her otherwise rigid rules. The majority of the detectives, in fact, attached little value to what they regarded as no more than anomalies of minor importance in the clues which they were following up. The difficulty, they argued, could be cleared up by giving to each element an atomic *number*, which indicated its place in the Periodic Table, and an atomic *weight*, which was the true indication of its identity. Thus argon was argon not because its atomic number was 18, but because its atomic weight was 39.944.

There were, however, some who did not feel at all happy about such conclusions. They had a suspicion that the investigators of the great "What is matter?" problem might well be barking up more than one wrong tree. Other fields of scientific inquiry probed by astronomers, biologists, geologists, botanists and mathematicians had found little evidence of untidiness in the great plans of Nature into which they were inquiring. Why, then, should she be lax in observing hard and fast rules about the constitution of matter?

For a long time no explanation could be found; but after Rutherford's discovery that each atom consisted of a

positively charged nucleus with negative electrons revolving round it the way was gradually paved for the solution of the difficulty.

Rutherford found that in every atom in its normal balanced state the number of orbiting electrons was the same as the number of positive charges on the nucleus. Each electron represented one unit of negative electricity and each of these negative units was exactly offset by one unit of positive electricity in the nucleus. Further, the number of these opposite electrical charges appeared to vary from element to element, but was always the same in all the atoms of any particular element. Every hydrogen atom, for example, had one orbiting electron and one positive charge on its nucleus; in every carbon atom there were six charges of each kind; in the magnesium atom, twelve; in the iron atom twenty-six; in the lead atom eighty-two. And curiously enough, the number of these charges was always equal to the atomic number.

The full significance of these facts was not realised until 1914, when H. G. J. Moseley, then only twenty-six years of age, caused something more than a flutter in the dovecotes of the scientific world by proclaiming that atomic numbers were something far more important than mere convenient indications of the places of elements in the Periodic Table. According to him, it was this number and not the weight of its atoms which identified one element from another. No one can say how brilliant Moseley's career might have been, for in the following year he lost his life in the Dardanelles; but it is certain that he made one of the most important discoveries in the whole history of the inquiry into the nature of matter.

Moseley's theory was proved correct by every subsequent advance in the investigation and it was the very foundation of all the discoveries about the atom and atomic energy that have since been made. What it comes

to is this: the weight of an atom may not give, as had previously been believed, a complete and unmistakable identification of the element to which it belongs; but the atomic number *must* give such an identification. Already scientists had been more than a little puzzled by the discovery that different kinds of lead could and did exist in the world. Though the atomic weight of lead in general had been determined again and again as 207.21, metals which were undoubtedly lead were found with atomic weights sometimes greater and sometimes less than 207.21. But no matter what this weight might be, the various leads all had 82 orbiting electrons and 82 positive charges on the nucleus and therefore an atomic number of 82.

There could be no doubt, then, that there were different kinds of lead. Was it possible that other elements had also more than one form? Later detective work was to show, as we shall see, that almost every element might occur in anything from three to a dozen or more different forms, each with its own atomic weight, but all with the same atomic number.

When we come to examine the methods used by scientific investigators up to the time of Thomson and Rutherford in the light of present knowledge, it is not surprising that they should have spent so many years in following up clues which, if not exactly false, could never lead to a full understanding of the nature of the atom. The difference between the investigators who were at work up to the time of Thomson and Rutherford and those who came after them was this. Nearly all of the scientific detectives of the era before these great discoverers tried to bring the secrets of the atom to light by using chemical methods. It was not until the investigation of the atom passed into the realm of physics, as it did with Thomson, Rutherford and their successors, that man had any chance of finding out how and of what kind of

component parts the atom was built up. Think of a single minute atom as enlarged to the dimensions of the solar system: then all that the chemists could hope to do was to discover something about the combined weight of all the bodies of which it was composed; something about the forces existing between these bodies and something about the behaviour of the outermost planets. Chemical methods might supply a fairly good general picture of the system as a whole, but they could not possibly furnish any detailed information about the nature of the most important member of the system—the Sun. For solar system read atom, for planets read electrons, for sun read nucleus and you have some idea of the shortcomings of purely chemical methods of investigation as applied to the atom.

Chemistry is concerned with the ways in which elemental atoms combine with one another to form compounds, or with the ways in which the molecules of compounds can be broken up into the atoms of elements. In either process the only parts of the atom concerned are the electrons revolving in the outermost orbits. These electrons are less tightly bound to the atom than those in orbits nearer the nucleus. No great force is needed to detach them from their atoms. When, for example, you press the switch of a pocket flashlamp the resulting chemical action within its battery causes in every second millions upon millions of atoms of one kind to lose temporarily two of their outer electrons and millions upon millions of those of other kinds to acquire temporarily outer electrons in excess of the normal number. So long as the switch is kept closed positive and negative ions are furnished by the chemical reactions within the cell.

All chemical processes occur mainly, if not entirely, through such gains and losses in the outer orbiting electrons of atoms.

The formation of a molecule of water from one oxygen

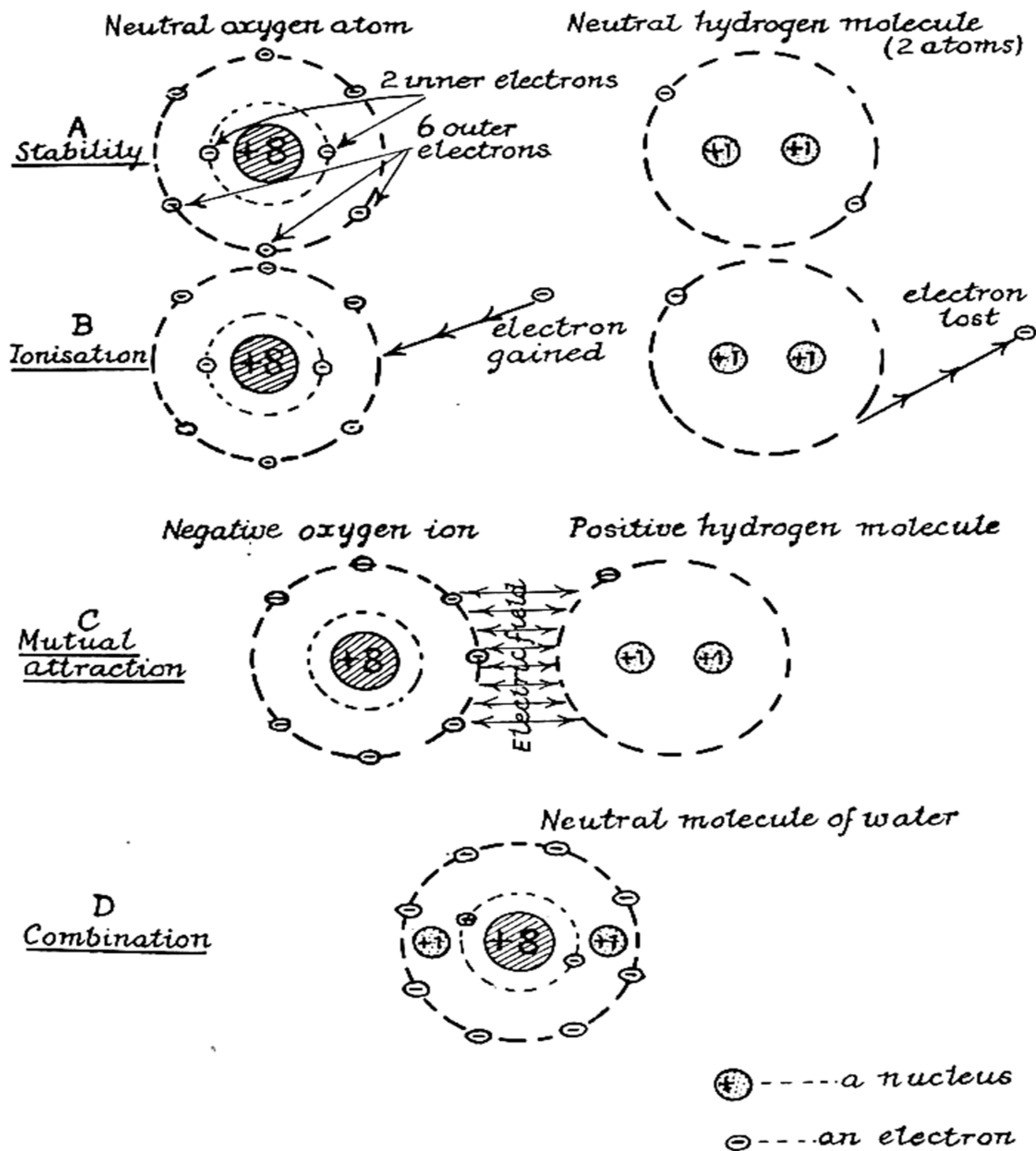


FIG. V.1. Showing how a molecule of water may be formed from two atoms of hydrogen and one of oxygen. Unless ionisation takes place the two gases simply form a mixture and do not combine. After ionisation combination of their atoms into the compound, water, occurs.

atom and a hydrogen molecule consisting of a pair of atoms may be visualised as taking place in the way shown in Fig. V.1. The drawings, remember, are purely diagrammatic: they are not to scale and the shapes of the electron orbits are represented as circles for the sake of convenience.

To begin with (at *A*) we have a neutral oxygen atom, with a nucleus containing eight positive charges counter-balanced by eight orbiting electrons, and a neutral hydrogen molecule, consisting of a partnership of two nuclei, each with a charge of $+1$, and two orbiting electrons. Notice that in the oxygen atom with its eight revolving electrons, the orbits are of two classes: the inner and the outer. The electrons in the former are much more tightly bound to the nucleus than those in the latter: enormous forces would be needed to detach either of the two inner electrons, but the six outer electrons are more loosely held and it is not difficult to detach one or more of them. Again, the electrons in the outer orbits may easily have their number increased, though the number of the inner electrons cannot be made greater than two. If these facts are borne in mind, the reason why only the outer electrons of an atom are affected by most of the combinations produced in the chemical laboratory will be clear.

The nuclei when such combinations cause compounds to be formed always preserve their identity.

In the second stage, seen at *B*, ionisation is being made to occur by exploding the mixture of gases or by some other of several possible means. The oxygen atom gains one additional outer electron and becomes a negative ion, for it now has eight positive charges in its nucleus and nine negative charges in its electrons. The hydrogen molecule parts with an electron and becomes a positive ion.

Between the two ions of opposite charge there now exists, as seen at *C*, an intense electric field. They attract

one another so strongly that they rush together and coalesce into the single neutral molecule of water shown in purely diagrammatic form at *D*.

Notice particularly (for this is going to be of great importance in later chapters) that this process of turning two things into a third thing nothing is in the end either gained or lost: there are exactly as many bits and pieces of exactly the same kind in the molecule of water as there

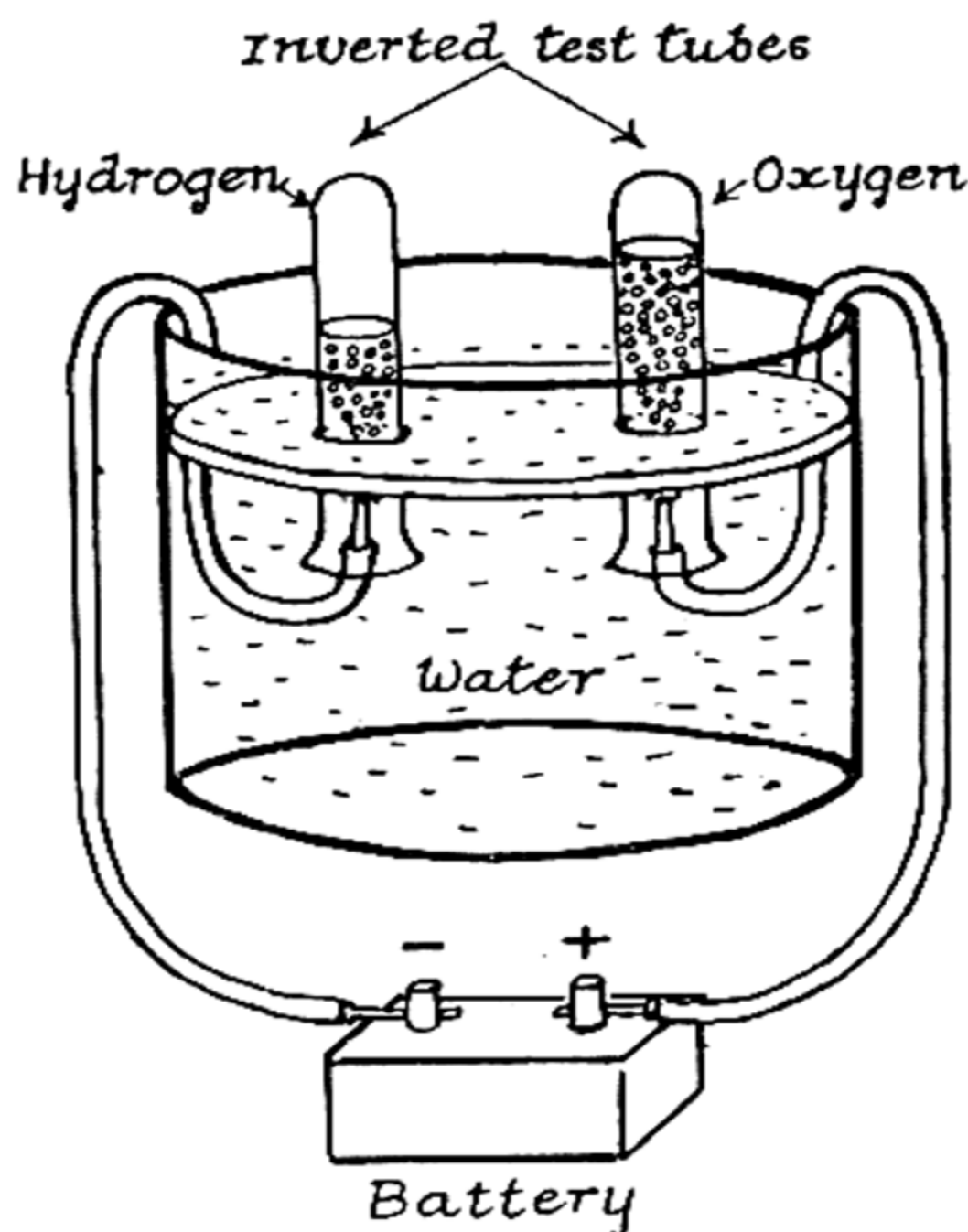


FIG. V.2. A simple experiment which shows that oxygen and hydrogen atoms do not lose their identity when combined into molecules of water. Water can be reconverted into the two gases in the way shown.

were in the original oxygen atom and hydrogen molecule. We started with eight positive charges in the oxygen atom and two positive charges in the hydrogen molecule: total, ten positive charges. We had also eight electrons in the oxygen atom and two in the hydrogen molecule: total, ten negative charges. In the neutral molecule of water we have ten positive charges and ten electrons.

A very simple experiment (Fig. V.2) shows, first, that

the original atoms do not lose their identity in forming a compound; secondly, that all the constituent parts of the atoms of which they are composed are present in the molecules of the compound; and, thirdly, that these molecules contain nothing else but the original nuclei and electrons. By passing an electric current through water we can cause it to break up, or decompose, into its constituent parts, the gases oxygen and hydrogen. Oxygen rises in bubbles from the wire connected to the positive pole of the battery, hydrogen from that connected to the negative pole. It will be found that the volume of the hydrogen obtained by the electrolysis (as the process is called) of water is always just double that of the oxygen.

In the laboratory carefully measured volumes and weights of the two gases can be converted into water by ionisation. If the water so obtained is reconverted into gases by electrolysis and precautions taken to make sure that none of either gas is allowed to escape, it is found that both the volume and the weight of both gases are unchanged.

We saw earlier that the smoking of a cigarette is a chemical process, in which the atoms of the tobacco and paper combine with oxygen from the air to form new compounds. The chief of these is carbonic acid gas, written in the chemist's shorthand as CO_2 —one carbon atom *plus* two oxygen atoms. If all the gases and the solids produced during the combustion of a cigarette are collected, they have together precisely the same weight as the original cigarette *plus* the oxygen used in the process.

These are but two examples. It is, however, always found in the chemical laboratory that when one substance is transformed by electrolysis, combustion or some other process into another substance nothing is either lost or gained. Matter cannot be destroyed; it can only be converted. Even the explosion of a ton of dynamite destroys

nothing. Every single atom of the original ton of solid explosive is present as an atom of gas or solid matter. If the dynamite had been used to "destroy" a mass of rock blocking the entrance to a harbour, no real destruction would have taken place. The rocks would no longer be there as great solid masses, presenting a danger to shipping. They would have been shattered into small, harmless fragments. Add together the weights of the atoms making up the gases and the solids produced by the explosion and they are exactly equal to those existing before it took place. Such a violent action as an explosion actually destroys nothing. What it does accomplish is a very rapid rearrangement of the millions upon millions of atoms concerned. The more rapid and complete the rearrangement, the more violent is the explosion.

It appeared, then, to Victorian scientists, whose investigation of the atom was mainly by the methods of the chemical laboratory, that matter was indestructible. It could be changed enormously in form. A gas could be frozen into a solid; a solid could be vaporised or exploded into gases, combinations of the atoms of elements could be made into compounds or unmade by analysis into atoms of elements. But, whatever was done, matter could neither be destroyed nor created. There were in the universe just so many atoms; that number remained unchanged, no matter what the combinations into which these atoms entered. The Conservation of Matter was held to be one of the basic principles of Nature.

A second basic principle was accepted by all the scientists of those days: the Conservation of Energy. Energy, they held, could be converted from one form to another, but it could not be created or destroyed. A piece of coal contains stored-up energy, collected millions of years ago by the tree or giant fern of which it then formed part from the heat energy received from the sun. That

store of energy can be released by burning the coal, which then gives back what was put into it by the sun. Use this to generate steam pressure in the boiler of a locomotive and you obtain just the original amount of energy in two forms. Part of it remains in the form of heat, which is dissipated into the atmosphere, but not destroyed; part of it appears as energy of motion, which enables the locomotive to haul a train. This energy of motion is, again, not lost but converted into other forms—mainly heat due to friction—as it is expended. When a piece of coal has been burnt in the firebox and the train has covered the number of yards for which it has provided the energy nothing has been lost. Under the principles of the conservation of matter, all of the original atoms can be accounted for, though they have gone to make up new compounds. The whole of the energy, so long stored up and now so quickly released, is also still in existence. Most of it has reappeared as heat-energy and the atmosphere of the entire world is a little warmer because the train has gone forward a few yards on its journey.

Though all the evidence available at the time furnished what appeared to be abundant proof of the truth of both of these principles, the detectives were later to find that neither was by itself correct. It was, as we shall see, to be discovered later that matter can be converted into energy and energy into matter. The principle of conservation is true; but matter and energy were later found, surprising as it may seem, to be different forms of the same thing.

Even at the stage which the investigation had reached the best part of a century ago it had been found that there was a significant interplay between energy and matter. When, for example, 1lb. of hydrogen combines with 8lb. of oxygen to form 9lb. (just under a gallon) of water the amount of energy, in the form of heat, concerned is enough to keep a one-bar electric fire going for about sixteen

hours. If your mains supply of electric current costs 2*d.* a unit (a "unit" is 1,000 watt-hours, or 1 kilowatt-hour), the production of this amount of water from the gases which make it up represents the energy contained in 2*s.* 8*d.* worth of current. To reconvert the 9lb. of water into oxygen and hydrogen by electrolysis sixteen units of electric power (2*s.* 8*d.* worth) would be required.

In the formation of water from oxygen and hydrogen this energy is expended in ionising the gases by causing the molecules of hydrogen to shed an electron apiece and become positive ions and by compelling each of the oxygen atoms to accept an extra electron and to become a negative ion.

It will be realised from what has been said that very considerable amounts of energy are in question when we are making changes in only the remote fringes of the atom; that is to say in its almost incredibly distant outer orbiting electrons. Far greater forces must surely be concerned if only some means could be found of upsetting the revolutions of the inner electrons in their orbits (for they are much more tightly bound to the nucleus), or of disrupting the nucleus itself. Could these things be done, something might be discovered not merely about the outer shell of the atom, but about that part of it—the nucleus—which contains not only nearly all of its mass, but also the particular characteristics which determine to which element any atom belongs.

Though they did not know it at the time, the detectives whose field of investigation was confined to the chemical laboratory could never hope to discover anything about the inner structure of the atom. As we have seen, all chemical reactions are due to the behaviour of the outer orbiting electrons of atoms: they do not affect the inner electrons or the nucleus. The chemists worked out their perfectly correct theory of valency. Though later discoveries showed that the number and arrangement of the outer

electrons was the real crux of the matter, the laws of valency were evolved long before the electron was discovered.

Put simply, the valency of an element is a measure of the number of hydrogen atoms with which one of its atoms can combine. Oxygen is bivalent because an oxygen atom can combine with a maximum of two hydrogen atoms: there cannot be such a compound as H_3O , since one oxygen atom cannot combine with three of hydrogen. If an element does not make compounds with hydrogen, its valency is assessed by the number of atoms of another element with which one of its atoms can combine. This is not the place for any detailed discussion of such a wide subject as valency. It will be sufficient to make and for the reader to remember, two points: (1) atoms can have valencies of 0, 1, 2, 3 or 4; those of elements with zero valency make no compounds and such elements are said to be inert; (2) the Periodic Table shows the elements not only in the order of their atomic numbers, but also in order of valency. All those in Group O have zero valency; those in Group I are univalent, those in Group II bivalent and so on up to Group IV.

So long as the atom was held to be some kind of tiny homogeneous body, a sphere consisting of one single form of matter, the methods of the chemical laboratory appeared to offer an entirely satisfactory way of investigating the nature of the atom. The discovery of the electron and, a little later, the discovery that atoms of radium could shoot electrons and other things as well out of themselves caused men of science to begin to realise that, though the chemists could supply some of the answers, they certainly could not provide them all. It was when the physicists took a hand in the investigation that new and unexpected clues were found one after another which led to entirely different ideas about the real nature of matter and of the atoms of which it is composed.

CHAPTER VI

Rutherford attacks the Problem

RUTHERFORD AND THOSE who worked with him and under his guidance and inspiration quickly saw that X-rays, electrons, and radio-activity offered completely new clues. The old conception of the atom as a tiny, solid sphere, which was the ultimate small speck of any kind of matter, had already been discarded. In its place the "miniature solar system" conception had come; and they could find no fault with that. Every atom had a central heavy nucleus, carrying a positive electric charge. Round this nucleus revolved a number of lightweight electrons, each with exactly the same negative electric charge. The number of these electrons, when the atom was in its normal neutral state and carried no electric charge of either kind, was exactly sufficient to counterbalance the positive charges on the nucleus. The chemists had already shown that if the atom was thrown out of balance by increasing or decreasing the number of the orbiting electrons, it still remained an atom of the same kind of matter.

You could, for instance, cause a neutral zinc atom to turn into a positive ion by removing two of its outer electrons; but what was left was still unquestionably an atom of zinc. To whatever treatment atoms were subjected in the chemical laboratory, their essential nature remained unchanged. To put it in another way, chemical methods did not allow atoms to be taken to pieces and examined. All that they could hope to do was to produce certain changes in the electrons which revolve in orbits far from the central nucleus and form a kind of shell round it.

If the answer to the question, What is matter? was to be found some means must be devised of breaking through this shell and of bringing about changes in the nucleus itself.

When Rutherford came to examine the alpha rays from radio-active elements he found that they were entirely different from the so-called beta and gamma rays. The gamma rays turned out to be rays indeed: they were electro-magnetic waves of shorter length and greater penetrating power than X-rays. The "beta rays" were proved by observing their deflection in electric and magnetic fields to be streams of electrons. When passed through similar electric and magnetic fields the "alpha rays" were deflected in exactly the opposite directions, which showed that their electric charge was not negative like that of electrons, but positive. The alleged "rays," then, were really streams of particles like the electrons of the "beta rays." But the particles had the opposite kind of charge and a long series of experiments and calculations showed that each of them carried *two* units of positive electricity. The investigations disclosed a still more surprising fact. Each particle weighed nearly 8,000 times as much as an electron and had about four times the weight of an atom of hydrogen. Rutherford reached the conclusion that there was only one thing that the particles could be: they must be the nuclei of helium atoms.

Let us see now how Rutherford set about his investigation of the inner parts of the atom and how he opened the way for those who came after him.

He had three important clues to work on:

(1) Radium, uranium and other radio-active elements were continually throwing away pieces of their atoms.

(2) These pieces consisted of heavy, positively charged particles (which appeared to be helium nuclei,

since they weighed four times as much as hydrogen atoms and had two units of positive charge) and electrons, representing units of negative charge. There were also the gamma rays; but these were radiation and not any kind of solid matter.

(3) The pieces discarded by the radio-active elements were fragments of their innermost parts—of their actual nuclei.

(4) In the process a genuine transmutation of elements must be taking place. Every time that a uranium atom hurled out an alpha particle it split its nucleus spontaneously into two nuclei, neither of which could be uranium. It was believed that the smaller fragment was a helium nucleus; this was subsequently confirmed by collecting and testing a quantity of these particles. The matter collected was found to be helium gas.

(5) Since the original nucleus had lost four units of mass by ejecting a helium nucleus, it appeared that the remaining part could no longer be uranium with an atomic weight of 238, but must be something with an atomic weight of $238 - 4 = 234$. No element of this atomic weight was then known.

(6) There were signs, soon to be confirmed, that a uranium nucleus did not cease from its activity after flinging out an electron, a nucleus or a train of gamma rays. It continued to discard parts of itself, making continual changes in its nature. Though there was a series of transmutations, they did not look like fulfilling the dreams of the alchemists. Instead of turning some base metal into gold, these spontaneous changes eventually transmuted one of the rarest of metals, uranium, into one of the commonest—the dull, prosaic lead! The long and remarkable series of changes leading to this strange result will be discussed in a later chapter.

(7) No chemical means could be found of starting, stopping, speeding up or slowing down these changes in a radio-active substance. No matter what was done to them in the chemist's laboratory, the breaking up of the nuclei of any radio-active substance always took place at the same fixed and immutable rate. As fresh radio-active substances were discovered it was found that the atoms of each had their own particular "rate of decay," a rate which never varied.

If the chemist could get no further inside the atom than its outer shell of electrons, would the detective in the physical laboratory be any more successful? Rutherford was quick to see that the physicist had real chances of success. With even the most powerful of microscopes the investigator can never hope to *see* an atom and still less a nucleus. How, then, can he possibly find out how it is made up?

Think of the discovery of the electron, described in Chapter IV. The electron was detected, identified, weighed and measured not by direct observation, but from the effects produced upon it by forces such as those of electric and magnetic fields and from the effects which it produced such, for example, as the visible glow on the screen of a cathode-ray tube due to bombardment by a shower of fast-travelling electrons. The physical methods used in investigation of the electron might be summed up as "treating it rough." Rutherford proposed to be still rougher in his treatment of the nucleus: His idea was to go one better than radio-activity. He would not wait for a radio-active nucleus to break up in its own good time: he would smash nuclei—and not necessarily radio-active nuclei—by shooting things at them and scoring direct hits. He could then collect the various bits resulting from the smashing and find out what sort of things they were. If

sufficient atoms of a particular kind could be broken up in this way, investigation of the *débris* should eventually show what the atoms were made of. It would be a long, laborious process, probably full of disappointments; but it must in the end give results. He was right. We do not yet know all that there is to be known about the constitution of matter; but we already know a great deal and fresh discoveries are continually being made. Most of these are due to investigations which are logical developments of the method originally suggested by Rutherford, the prince of scientific detectives.

What was he to use for bullets in shooting at nuclei? Could a shooting range furnished with targets be devised? How could the effects of a direct hit be observed and measured? What were the chances of making such a hit? His earlier investigations were made by firing alpha-particles through sheets of foil; but some better method was needed and later he and his assistants found it. The fast and heavy alpha particles ejected by radio-active elements provided an inexhaustible supply of ammunition. The laboratory already contained a suitable shooting range in the form of the cloud chamber, invented by C. T. R. Wilson and used by Thomson in his investigation of electrons. The targets would be the nuclei of gas atoms in the cloud chamber. In the chamber the flying alpha-particles would leave visible tracks, which could be photographed. From the shape and length of the photographed tracks it should be possible to discover a great deal about the nature of the fragments due to a direct hit.

The chances of scoring a direct hit with any alpha-particle bullet were admittedly quite small. The atoms of any gas within the chamber are widely separated from one another. Each nucleus in the gas is guarded by its protective shell of electrons, which resists the entry of any

body from outside. In addition to all that, the atom itself is, as we have seen, mainly "full of emptiness"; magnify an average atom to the size of a football and its nucleus is still a microscopic speck. Bullets which succeeded in penetrating the case and the bladder of the football might pass right through it without going anywhere near the nucleus. It was, in fact, probable that a large proportion of them would do so. The bullets, remember, were helium nuclei, carrying two positive electrical charges. The nuclei of the gas atoms in the chamber were also positively charged—and like charges of electricity repel one another. To score a bull's-eye on a nucleus an alpha particle would need to approach a gas atom from exactly the right direction and to be travelling fast enough to penetrate the electron shell and to overcome the enormous repulsive forces between the nucleus and itself. The odds against a direct hit were millions to one. Still, if you fired vast numbers of alpha particles at vast numbers of nuclei of gas atoms it was certain that a bull's-eye must eventually be scored. P. M. S. Blackett, now famous for his contributions to atomic research and a Nobel Prize-winner, took more than twenty thousand photographs of the laboratory shooting range before the historic picture which appears as *Plate 1* was obtained.

The reader is most likely wondering what kind of thing is the Wilson Cloud Chamber which acted (and still acts) as the shooting range for the marksmen of the atomic laboratory. Like so many of the most ingenious and useful inventions, it is a comparatively simple affair. The chief parts of the apparatus are shown in simplified form in Fig. VI.1. The principle is this. If a quantity of any gas containing a large amount of moisture is suddenly expanded, very rapid cooling takes place and the gas becomes super-saturated with moisture. In this condition it has a strong tendency to condense and form tiny drops;

but it cannot do so unless the gas contains specks of matter. Any little piece of matter, however minute, is sufficient to set the ball rolling, so to speak; a tiny amount of moisture forms a droplet surrounding it, just as a cultured pearl is formed in the shell of an oyster by the deposit of hard matter round the little bit of grit introduced by the pearl grower to act as a core. A minute

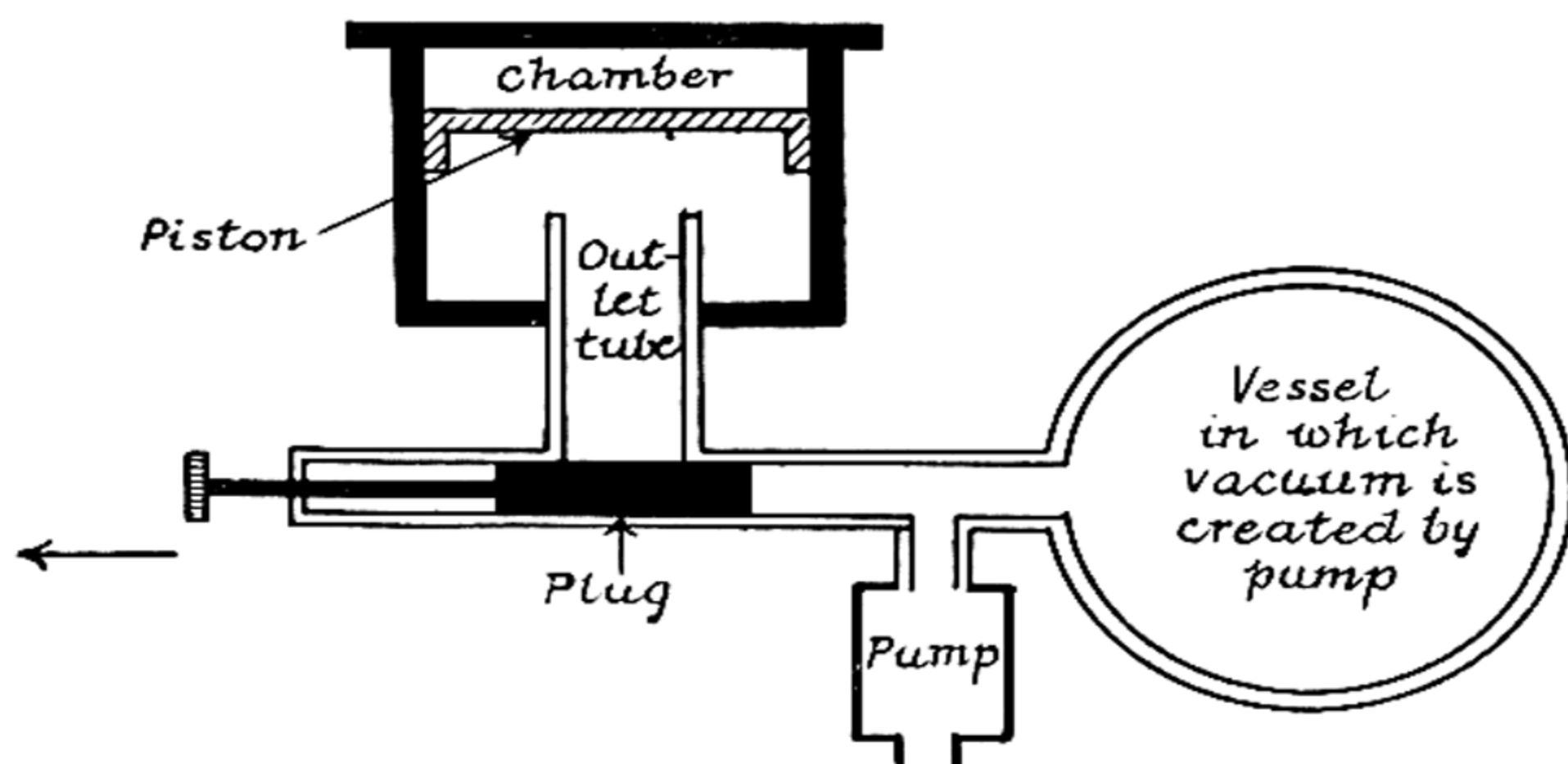


FIG. VI.1. Simplified drawing, showing the principles of the Wilson cloud chamber, one of the most useful tools of the atomic investigator.

charged particle, such as a positive or negative ion, will serve as a core and allow condensation to take place. The droplet of moisture formed round it is millions of times larger than the original particle; big enough, in fact, to be seen or photographed.

Suppose that an alpha particle (helium nucleus) is shot into the gas after it has been cooled. Though it may make no direct hit on a nucleus, it disturbs the outer electrons of vast numbers of atoms as it flies and so turns these atoms into charged particles, or ions. Each of them acts as the core of a droplet of condensed moisture. The result is that though we cannot see the alpha particle, we can see the exact path taken by it from the trail of visible droplets left in its wake. If a head-on collision with a nucleus does

take place, the paths of the resulting fragments are also plain to see.

How is all this going to be done? The chamber in Fig. VI.1 is first of all very carefully cleaned so that not the smallest mite of dust remains in it. It is then filled with air, or some other kind of gas, with a large proportion of moisture. The plug in the position seen in the drawing completely closes the outlet tube. The pump is now started and produces a vacuum in the spherical vessel. When the vacuum is sufficient the rod attached to the plug is pulled in the direction of the arrow. This opens the outlet tube, through which air rushes to replace the vacuum in the evacuated vessel. A partial vacuum is thus left below the piston, which forms the bottom of the chamber. The piston is suddenly drawn down, enlarging the chamber and expanding the gas within it. If a stream of alpha particles is now shot into the chamber the tell-tale condensation tracks are produced in it.

Much could be learnt about the helium nucleus by recording and measuring the tracks through the chamber and making careful calculations based on the data provided by deviations and the results of head-on collisions. To take an analogy, which must not be pressed too closely, detectives tracking an unknown suspect who had run fast over a firm, sandy beach could discover a great deal about the weight, height and build of their man by measuring the size and depth of his footprints and the length of his strides. If in his haste he collided violently with an obstacle and tore open some of his pockets, a great deal about his character and habits might be deduced from what fell from these and from his hands and was left behind in his half-stunned state. A butterfly net, a pocket magnifying glass and an entry card for the British Museum Reading Room would indicate quite a different kind of person from one who dropped a couple of pawn tickets,

the remains of a half-bottle of gin and a bundle of betting slips, or, again, from one whose leavings included a black mask, a bunch of skeleton keys and some counterfeit coins.

But the shooting of alpha particles at nuclei was destined in Rutherford's hands to do far more than provide shreds of information about the bullets and their targets; it was to lead to a further realisation of the old alchemists' dream: the artificial transmutation of one element into another. Radio-activity had shown that transmutation occurred naturally. Aided by James Chadwick (now Sir James Chadwick) Rutherford set out to find a means of producing the transformation of an element in the laboratory. He had observed that when alpha-particles were shot through hydrogen, head-on collisions produced lighter particles which travelled farther and faster than his bullets. Careful investigation showed these to be protons, the nuclei of hydrogen atoms. He decided to use nitrogen atoms as his target. Again the fast "knock-on" protons were driven from the gas. Repetitions of the experiment, close observation and calculations checked and rechecked left no doubt that the helium nucleus forming the alpha particle and the nitrogen nucleus with which it collided were broken up and that the particles of which they were built were rearranged to form two entirely different nuclei. One of these was hydrogen; the other, oxygen. All of the original bricks of the helium and the nitrogen nuclei were still there; none had been added to them. But the collision had caused them to be regrouped in a new way and they now built up the nuclei of two quite different elements. We shall see a little later how regroupings of the nuclear bricks take place in this and other transmutations of elements.

Different Kinds of the Same Thing!

THE PERIOD BETWEEN THE two world wars is sometimes called the wasted years. That the years from 1919 to 1939 were spent aimlessly and unprofitably by a large part of the human race is a matter about which there can be no doubt; but nothing of the kind occurred amongst the physicists engaged in the Cavendish Laboratory at Cambridge and other centres where inquiries into the nature of matter went forward, particularly in France, Denmark, Holland, Germany and the United States. Far from being wasted, these years were amongst the busiest and the most productive in the whole history of the great investigation.

For some time before the close of his active career Rutherford had felt that there must be other bricks besides electrons and protons used in the building of matter. In their experiments with the cathode-ray tube, the cloud chamber and other tools of the physical laboratory he and other scientists in this country and elsewhere found an increasing number of effects which could not be satisfactorily explained if the atoms of matter consisted simply of groupings of protons and electrons.

In 1932 one of the many disciples upon whom Rutherford's mantle was to fall and who are still carrying on the great work which he began made a discovery which was to revolutionise all theories about the atom and to lead to an entirely new conception of the way in which the different kinds of matter are built up of tiny particles common to all.

Chadwick, to whose earlier work reference was made in the last chapter, announced in 1932 the discovery of a new brick which differed fundamentally from the electron and

the proton in having neither a positive nor a negative charge. Since it had no charge at all and was therefore electrically neutral, it was named the neutron. The neutron has approximately the same weight as the proton, or hydrogen nucleus. It is not surprising that its discovery should have lagged so far behind those of the electron and the proton. Since they have electric charges, the electron and the proton are deflected when they are passed through electric or magnetic fields and the effects of such deflections can be studied, as we have seen, in the physical laboratory. But the neutron, having no charge, is unaffected by the bullying to which the physicist subjects the electron and the proton; hence the use of these methods alone could not disclose the presence of the neutron. But they could and did cause certain secondary effects to occur on a scale so small that they might pass unnoticed—or be regarded as having no special importance—by any but the most painstaking, the most observant and the most acute of detectives in the physical laboratory.

Laboratory workers had long been puzzled by some of the tracks shown in cloud chamber photographs. These tracks, remember, can be made only by a charged particle; for this in its passage through the gas in the chamber makes ions, which act as cores upon which tiny drops of moisture condense. Fig. VII.1 shows the kind of photograph which provided a clue to the discovery of the new particle of matter. An alpha particle entering the cloud chamber at *A* leaves the visible condensation track *AB*. At *B* it collides with a nucleus, from which a charged particle is driven out, making the visible track *BC*. Another visible track, indicating a second collision at *D* and the ejection of another charged particle, is seen to run from *D* to *E*. No charged particle can have caused that collision, or it would have left a visible track from *D* to *E*. How, then, could this second collision possibly have happened?

Chadwick's brilliant inference was that it must have been caused by an uncharged particle, of the same size and mass as a proton, ejected from B during the first collision and following the invisible track BD indicated by the broken line. In cloud chamber photographs there

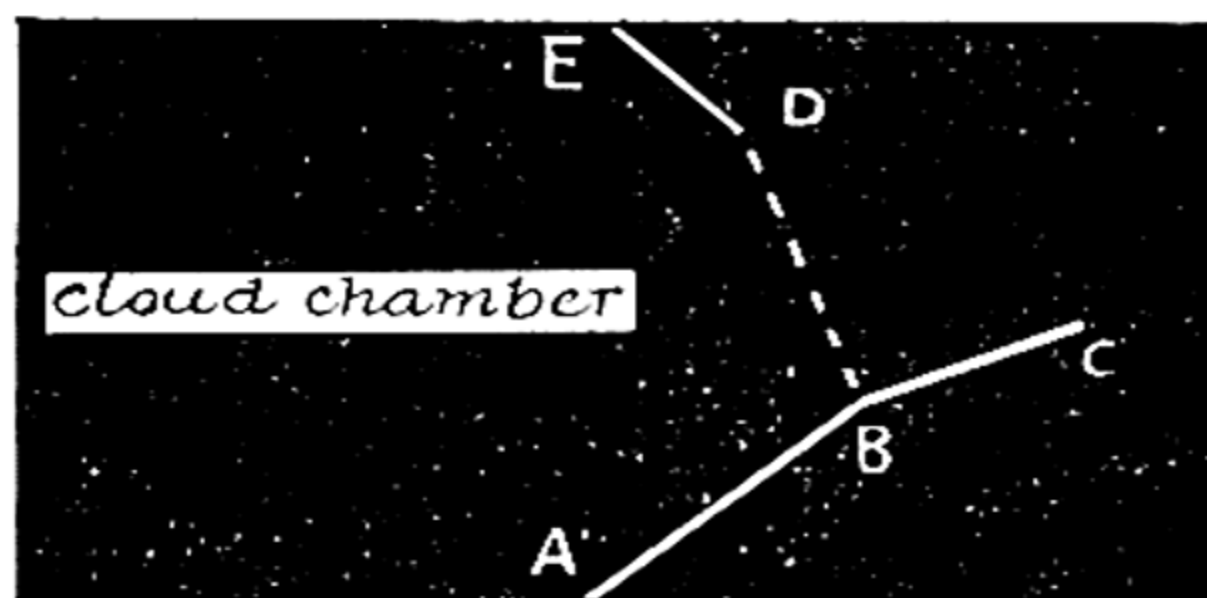


FIG VII.1. A typical cloud-chamber photograph of this kind led to Chadwick's discovery of the neutron. The broken line BD does not, of course, appear in the photograph. As explained in the text, *something* ejected from the first collision at B leaves no track, but causes a collision at D . As there is no condensation track from B to D , the particle causing the second collision must have no electric charge. It is, in fact, a neutral particle, or neutron.

was nothing to show that track, for an uncharged particle makes no ions as it travels and therefore provides no cores for droplets of moisture. Chadwick's genius supplied, so to speak, the broken line in Fig. VII.1 and brought to light the invisible track of the unknown particle.

Countless experiments of many kinds were needed to confirm the existence and the nature of the new particle, which proved to have extraordinary characteristics. Having no charge, it was neither attracted nor repelled by the electrons and the protons of atoms. If a nucleus happened to be right in its path as it travelled, it could collide with it head on; but the odds against such a meeting were very great. In the ordinary way a flying neutron either passed unhindered between the atoms of a gas, or even a solid, or went through some of them. Through them? Yes, a neutron may pass between the orbiting electrons and the nucleus of an atom without hitting anything much as a

comet can pass through our solar system. For these reasons its penetrating powers are astonishing. A neutron can travel a considerable distance through solid lead.

We do not yet know all the results that may follow from the discovery of the neutron. It has already led to an entirely new conception of the nature of the atom and of matter; it has explained the apparent discrepancies of the periodic table; it has opened new fields in chemistry and physics; it has shown the way to the use of atomic energy; it has enabled entirely new elements, which have probably never existed in nature, to be manufactured in the laboratory. What it may still have in store for us of good or evil no one can yet say. Well used, the discovery may give man untold benefits; ill used, it may wreck civilisation.

It is interesting to note that the conception of the atom due to Rutherford pointed to the apparent correctness of Prout's long discarded theory that all matter was built up from "protyle," or hydrogen atoms. The hydrogen atom consists of one proton and one electron. According to Rutherford, every atom, taking the nucleus and the orbiting electrons together, consisted of an equal number of protons and electrons. It could thus be regarded, without too great a stretch of the imagination, as a complex assembly of hydrogen atoms.

The modern idea of the nucleus (Fig. VII.2) is that it contains no individual electrons, but consists entirely of neutrons and protons. The atomic number thus indicates the number of protons in the nucleus of the element to which it refers. Each proton has one-sixteenth the weight of an oxygen nucleus. The difference between the atomic weight of an element and its atomic number shows the number of neutrons that its nucleus contains . . . or, rather, it would do so if every atom of a particular element contained the same number of neutrons.

We have already seen how from the time when atomic

weights began to be measured accurately scientists had been sorely puzzled by the fact that very few of these were whole numbers, no matter what the unit on which they were based. It was eventually decided to base tables of atomic weights on the assumption that the oxygen

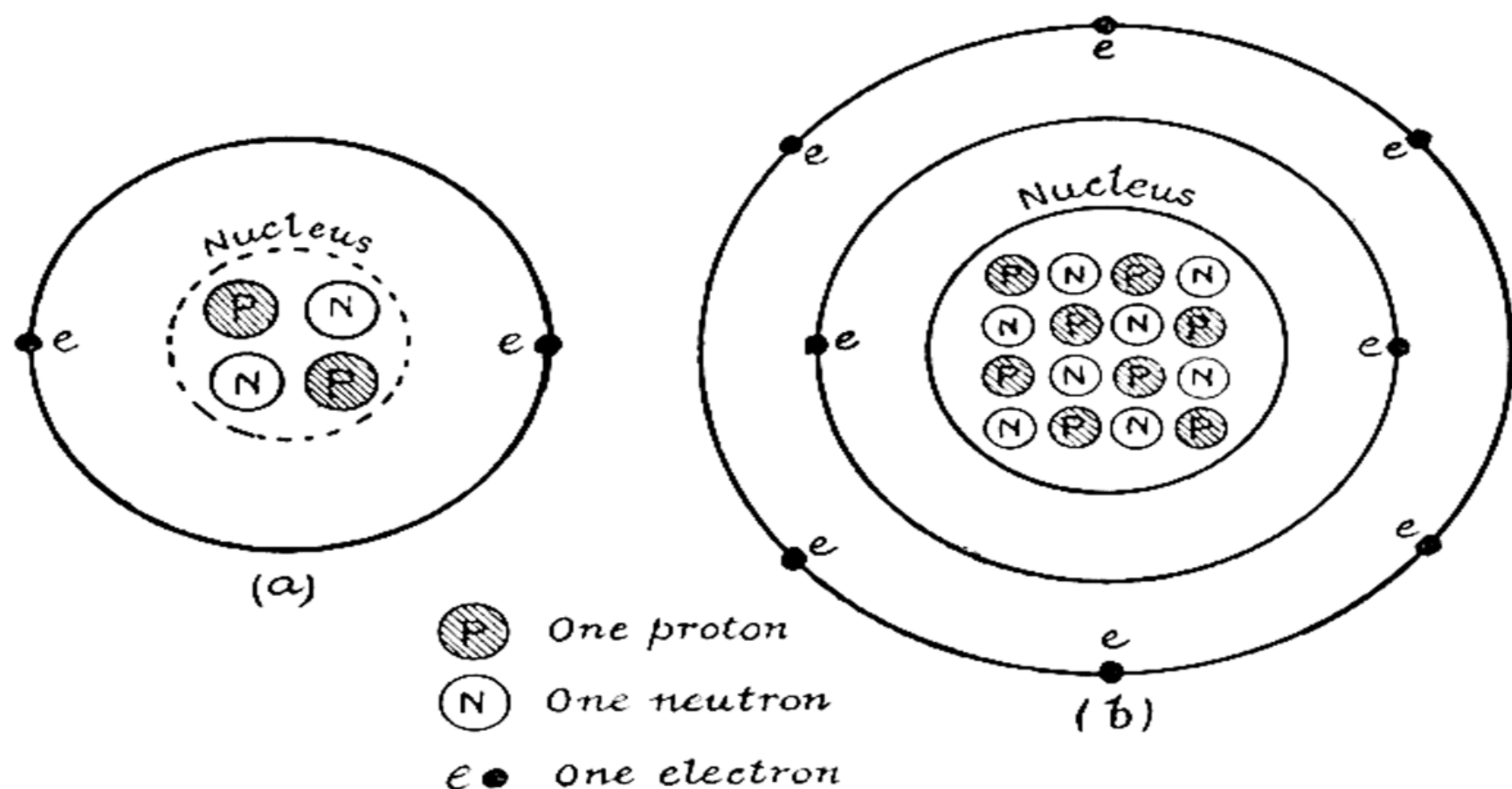


FIG. VII.2. Modern views of the composition of (a) the helium and (b) the oxygen atom. It is now believed that the nucleus contains no "free" electrons. Compare Fig. VII.2(a) with Rutherford's conception of the helium atom seen in Fig. IV.4(b).

atom had sixteen units of weight or mass. The tables drawn up on these lines are still in use by chemists to-day and there is no question of the complete accuracy of the figures that they contain.

Then, how can the difference between the atomic weight of, say, silver and its atomic number show the number of neutrons contained in the nucleus? The atomic weight of silver is 107.88; its atomic number is 47 and the difference between the two is 60.88. Surely you cannot have 0.88—eighty-eight hundredths—of a neutron? You can't: protons, neutrons and electrons are units of matter and

always appear in whole numbers in any atom. Then how are we to explain those untidy looking decimal places in the atomic weights of silver and other elements?

The truth is that almost every known element may have several different forms. Everyone nowadays has heard of heavy hydrogen. Most elements have heavy forms and some have light forms as well. By far the commonest hydrogen atom contains one proton balanced by one electron and has an atomic number of 1 and an atomic weight of 1. But roughly one hydrogen atom in every 5,000 has a nucleus consisting of one proton *and* one neutron. Such atoms still have an atomic number of 1, but their atomic weight is 2. Similarly, all silver atoms have an atomic number of 47, because all contain forty-seven protons; but some contain sixty neutrons and have an atomic weight of 107, whilst others contain sixty-two neutrons and have an atomic weight of 109. In the chemical laboratory these different kinds of hydrogen, silver and so on are indistinguishable, for all behave in exactly the same way and have precisely the same chemical properties. They were thus undetectable by chemical methods.

Any sample of an element contains the same proportion of "normal," "heavy" and sometimes "light" atoms. Hence the atomic weight obtained from it is the *average* weight of its atoms and not the individual weight of each one of them. The reason for the apparently untidy atomic weights of the periodic table now becomes plain.

Other difficulties are also cleared up. One of these is that argon and potassium are placed in the periodic table in the order of their atomic numbers, but not in that of their atomic weights. Argon, though of higher atomic weight, comes before and not after potassium. The reason is that any sample of argon contains a comparatively large proportion of "heavy" atoms, whilst there are many

“light” atoms in a sample of potassium. Hence their *average* atomic weights are not in the same order as their atomic numbers. The reasons for the apparent topsyturvyness of cobalt and nickel and of tellurium and iodine in the table are similarly explained.

There are, then, different forms of elements with different weights, just as there are various kinds of various weights of potatoes or motor cars or dogs. But no matter whether it is light or medium or heavy, a potato cannot be anything but a potato or do anything more or less than a potato can do. So with motor cars and dogs. So, again, with atoms. Atoms are identified once and for all by their atomic numbers: that is, by the number of protons that their nuclei contain. If an atom has eighty-two protons in its nucleus it *must* be lead, no matter what it weighs; and if a nucleus contains eighty-two protons it *must* be the nucleus of a lead atom, no matter how many neutrons it has in addition. Actually there are ten known kinds of lead with atomic weights running from 204 to 214, with a gap at 205.

The different forms of an element are known as its isotopes.* The word is of modern coinage from the Greek *isos*, equal, and *topos*, place. It signifies that all the varieties, or isotopes, of any particular element belong to that element's compartment in the periodic table. The atomic weight of any particular isotope is known as its mass number. Thus 204 is the mass number of the isotope of lead containing eighty-two protons and 122 neutrons. The existence of some isotopes was known before the discovery of the neutron. J. J. Thomson, for instance, had found at the outbreak of the First World War that there were different kinds of neon. But not until the neutron was discovered could the nature of isotopes be fully understood.

* For a description of the Mass Spectrograph by means of which F. W. Aston investigated isotopes see Appendix A, Section 1.

In view of what we have now seen about neutrons, about the modern idea of the nucleus and about isotopes, it is worth while to return briefly to the first artificial transmutation of matter, described in Chapter VI, and to see what happened when Rutherford and Chadwick produced head-on collisions between helium nuclei (alpha-particles) and nitrogen nuclei. The results of the collision are illustrated diagrammatically in Fig. VII.3.

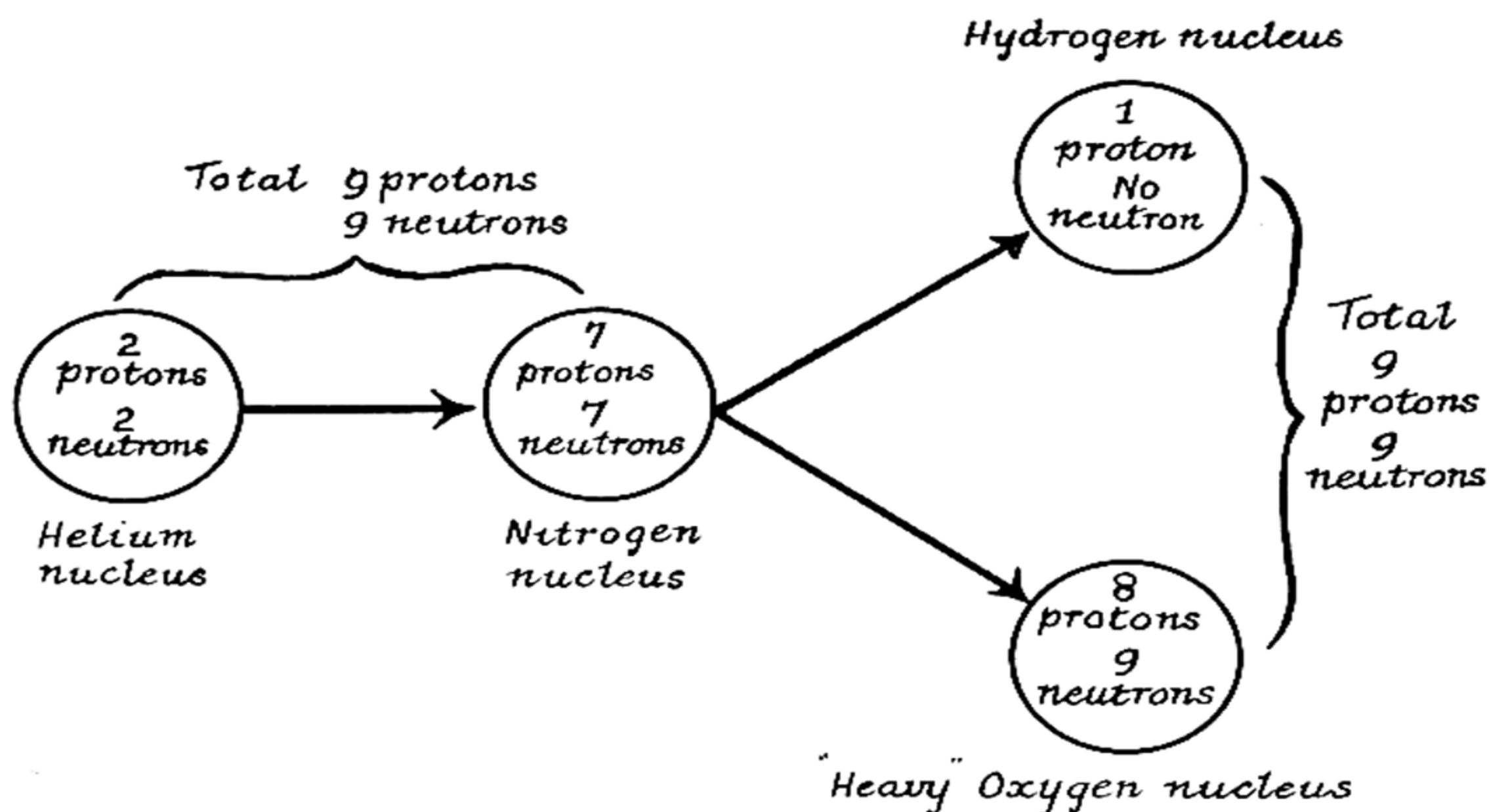


FIG. VII.3. The results of a head-on collision between a helium nucleus (alpha-particle) and a nitrogen nucleus shown diagrammatically. Two different elements are formed, but all the original "bricks" are accounted for.

To begin with we have the helium nucleus, consisting of two protons and two neutrons, and the nitrogen nucleus, consisting of seven protons and seven neutrons. The violent impact of the first on the second produces a regrouping of the available nine protons and nine neutrons, with the result that nuclei of entirely different elements emerge from the collision. One of these is a hydrogen nucleus, consisting of a single proton, with no

neutron at all. The second is a "heavy" oxygen nucleus, with eight protons and nine neutrons. There is neither loss nor gain in the number of positive charges (protons); neither loss nor gain in the number of units of mass (protons and neutrons). We began with:

	<i>Positive Charges (Protons)</i>	<i>Units of Mass (Protons and neutrons)</i>
1 Helium nucleus	2	4
1 Nitrogen nucleus	<u>7</u>	<u>14</u>
Total	<u>9</u>	<u>18</u>

After the collision we have:

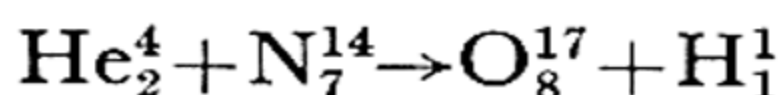
1 hydrogen nucleus	1	1
1 "heavy" oxygen nucleus	<u>8</u>	<u>17</u>
Total	<u>9</u>	<u>18</u>

The atomic physicist uses a neat and simple shorthand way of representing these things. He describes any atom by means of its international symbol and two numbers written in small figures, one up aloft and the other down below. If you want to be correct and formal, you can call the upper small figures "superscripts" and the lower "subscripts."

The upper, or mass number shows the total mass or weight of the nucleus: that is, the total of protons and neutrons within it. The mass number is usually slightly different from the atomic weight for any particular element because it indicates not the average weight of a sample containing various isotopes, but the atomic weight of one particular isotope. Thus the symbol for nitrogen is N and its atomic weight is 14.008; but no less than four different forms of nitrogen are known and the physicist shows which of them he means by calling it N^{13} , N^{14} ,

N^{15} or N^{16} . The lower number is the atomic number, showing the number of positively charged protons in the nucleus—or that of the orbiting electrons which counter-balance them in the neutral state. This number never changes for any element; it is, in fact, the identity card of that element. Nitrogen has seven positive charges on its nucleus and, conversely, any atom with seven positive charges must be an atom of nitrogen and cannot be anything else.

The collision between the alpha particle and the nitrogen atom and its after effects are shown in the shorthand form as



The commonest form of oxygen has a nucleus containing eight protons and eight neutrons O_8^{16} . But oxygen has both “light” and “heavy” isotopes. There are five known oxygen isotopes: O_8^{15} , O_8^{16} , O_8^{17} , O_8^{18} and O_8^{19} . You will see that the atomic weight is not, as earlier scientific detectives had supposed it to be, anything like an infallible indication of the nature of an atom. Actually there are nitrogen isotopes with masses of 15 and 16 units, fluorine isotopes with masses of 17, 18 and 19 and a neon isotope with a mass of 19. Five atoms with masses of 15, 16, 17, 18 and 19 respectively *might* have among them those of nitrogen, oxygen, fluorine and neon if there was nothing but their weights by which to identify them; but if each of the atoms has eight positive charges, all must be oxygen atoms. If any belonged to nitrogen, they could be only N_7^{15} and N_7^{16} . The only possible fluorine atoms within these masses are F_9^{17} , F_9^{18} and F_9^{19} . For an atom of mass 19 to be neon it would have to have ten positive charges on its nucleus and would be the “light” isotope Ne_{10}^{19} . The three atomic particles that we have discussed can be written in the same shorthand. The proton is either H_1^1 or p_1^1 ; the neutron n_0^1 and the electron e_1^0 . The mass of the

electron appears as 0 because it is insignificant in comparison with neutron or proton.

Notice that in the shorthand statement of the results of the collision of the alpha-particle with the nitrogen nucleus, and in any other similar statement, the superscripts must always add up to the same total on both sides of the arrow: $4+14\rightarrow18$; $1+17\rightarrow18$. In the same way the subscripts must balance exactly: $2+7\rightarrow9$; $8+1\rightarrow9$. This shows clearly that the mass units (protons and electrons) with which we started are simply regrouped in the transmutation of two elements into two others. All of them are still there when the process is complete and no fresh ones have been added. Similarly, the nine original positive charges are all still there without loss or addition: we began with nine and we end with nine. *Plus ça change*, in fact, *plus c'est la même chose*. Whatever changes are brought about in the laboratory, all the original bits and pieces are still present. We do not yet know how to reverse the process artificially and to turn oxygen and hydrogen back again into helium and nitrogen, but it must be possible to do so, for all the ingredients are there.

Such transmutations or regroupings, without loss of mass, appear to show the truth of the principle of Conservation of Matter (mentioned in Chapter V), which amounts to this: the Universe contains, has always contained and will go on containing the same definite amount of matter; new matter cannot be created; existing matter cannot be destroyed. Another principle, once believed to be one of the fundamental laws of Nature, is that of the Conservation of Energy. This holds that energy, like matter, is convertible into various forms but is never destroyed and that no increase or decrease of the total amount of energy existing in the Universe can take place.

As we shall see a little later, these principles have had to be revised in a completely unexpected way.

CHAPTER VIII

The Orbiting Electrons and Radiation

HOW DOES A POKER that has been left in the fire for some minutes give out heat when it is withdrawn? Why does it emit light when it is taken from a fire sufficiently fierce to make it become red-hot or even white hot? How, again, does the fine wire that can be seen inside the bulb of a clear-glass electric lamp send out the light which may be enabling you to read this chapter? The scientific detectives of the last century thought that they had found complete answers to these questions by saying that the heat from the fire set the atoms of the poker into a state of agitation, in which they emitted radiation. If the agitation was not very violent, they radiated a small amount of heat. As its violence was increased the radiation became of shorter and shorter wavelength until it produced visible light first red and, if the heating up process were continued, subsequently orange, yellow and eventually a yellow pale enough to be called white. As for the filament of the electric lamp, they were satisfied that the passage of any electric current through a wire agitates the atoms of the wire. Make the current heavy enough in relation to the diameter of the wire, and the agitation becomes sufficient to cause the radiation of light.

All of this is correct up to a point; but it does not explain just how the radiation is emitted or why it should be of a particular wavelength. We shall come to the new ideas on the subject in a moment; but we had better clear up first of all what we mean by radiation. Radiation may be described as the conveyance of energy, such as light or heat, by electro-magnetic waves. Other energy-conveying

waves of this kind are those of wireless, X-rays and gamma rays. All kinds of electro-magnetic waves have one thing in common: they travel at the speed of 300,000,000 metres, or 186,200 miles a second.

The wavelength, measured in metres, centimetres, millimetres, or minute fractions of millimetres, is the distance between the "crests" of two consecutive waves. A complete wave—crest and trough,—is called a cycle and occupies one wavelength. The frequency is the number of waves that occur in one second. If you know the wavelength you can find the frequency and *vice versa*,

for frequency = $\frac{300,000,000}{\text{wavelength}}$ cycles a second and wave-

length = $\frac{300,000,000}{\text{frequency}}$ metres. The shorter the wavelength,

the higher the frequency; the lower the frequency, the longer the wavelength. From now on we will use frequencies in classifying electro-magnetic waves; but this should not cause any difficulty if the relationship between frequency and wavelength is borne in mind.

The kind of energy conveyed by a train of electro-magnetic waves depends entirely on the frequency. Those of the lowest frequency class (from about fifteen thousand to thirty thousand million cycles a second) are sent out by wireless transmitters and detected by wireless receivers. Next in order of frequency come heat waves, then light waves, then X-rays and above them the gamma rays.

It used to be thought that energy was brought in a continuous stream by electro-magnetic waves, though in the seventeenth century Newton had advanced his Corpuscular Theory of Light. This, however, gained no general acceptance. At the beginning of the present century the great German physicist, Max Planck, announced the results of an entirely new line of inquiry. Energy, such

as light, he showed, does not flow in a continuous stream from its source to the eye; it is conveyed in separate little packets. Each packet is called a quantum (plural, quanta) and the energy of any quantum is found by multiplying the frequency by a fixed and unvarying number, known as Planck's constant. This gives the answer in ergs per second—and an erg is one ten-thousand millionth (10^{-10}) of a kilowatt. When one bar of an ordinary electric fire is switched on it is heated by one kilowatt of electricity. It will be seen then that an erg is something very small. But Planck's constant is the minute number 6.624×10^{-27} . It will be seen, then, that frequencies of a few thousands or even millions of cycles a second have quanta of very tiny energy indeed. The energy per quantum increases as the frequency is increased; but even when we come to gamma ray frequencies such as one hundred million million million (10^{20}) cycles per second the quantum is almost incredibly small, though it is thirty thousand million times as great as that of the shortest wireless waves!

The quantum is the unit of energy for radiation of any particular frequency. Whatever that frequency may be it can convey energy in equal-sized packets only; you cannot have a fraction of a quantum, any more than you can have a fraction of an electron. The packets vary in size according to the frequency, but for any one frequency all quanta have the same value.

The way in which the quantum theory fits in with events occurring within the atom was worked out by Planck and Einstein in Germany, by Nils Bohr in Denmark and by Rutherford and his team in this country. It was a long business, a combination of genius and hard slogging. The outstanding figure in this stage of the inquiry is Bohr. His theory of the arrangement of electrons within the atom seemed for a good many years to give a complete picture of the way in which radiation of different

kinds was produced. It has now been to a large extent superseded, since it did not meet all the requirements of advanced physics and mathematics. The most recent views are based on wave-mechanics, a branch of the higher mathematics which defies any kind of simple explanation. A great mathematician, in fact, once told me that he did not fully understand the meaning of some of his own equations in wave-mechanics! He knew that they contained truths. Some of these he could comprehend; but others were still beyond his understanding. Even if I were able to do so, I should have no wish to present the reader with headaches of that kind! Bohr's theory of the atom is not incorrect; it provides a means of picturing the electron arrangement of atoms which fits in with the quantum theory. To mathematicians of the highest order it is inadequate because their obtruse calculations indicate that there is something beyond its conceptions. But neither I, nor, I expect, the reader are mathematicians of such a calibre; for us Bohr's picture of the atom, now to be discussed, supplies everything needed to explain the phenomenon of radiation.

In Fig. VIII.1 the outlines of this picture are shown in diagrammatic form. The nucleus is surrounded by seven layers or "energy levels" into which all the possible orbits of the electrons are grouped. The electrons of an atom are not free to revolve at any distance from the nucleus that takes their fancy: the orbits that they may occupy are definitely fixed. There are no intermediate stages between them. An electron could not have an orbit which was, let us say, half way between the innermost energy level and the one next beyond it; its orbit must be in one or other of the rings which represent these levels in Fig. VIII.1.

The electron, in fact, is governed as regards its distance from the nucleus and the shape of its orbit by rules very similar to those which regulate the places occupied by the

members of the audience in the theatre. Playgoers are shown into seats in the gallery, the pit, the upper circle, the dress circle, the stalls or the boxes according to the entrance fee that they have paid. The relative goodness of a seat depends upon the price paid for it. Money

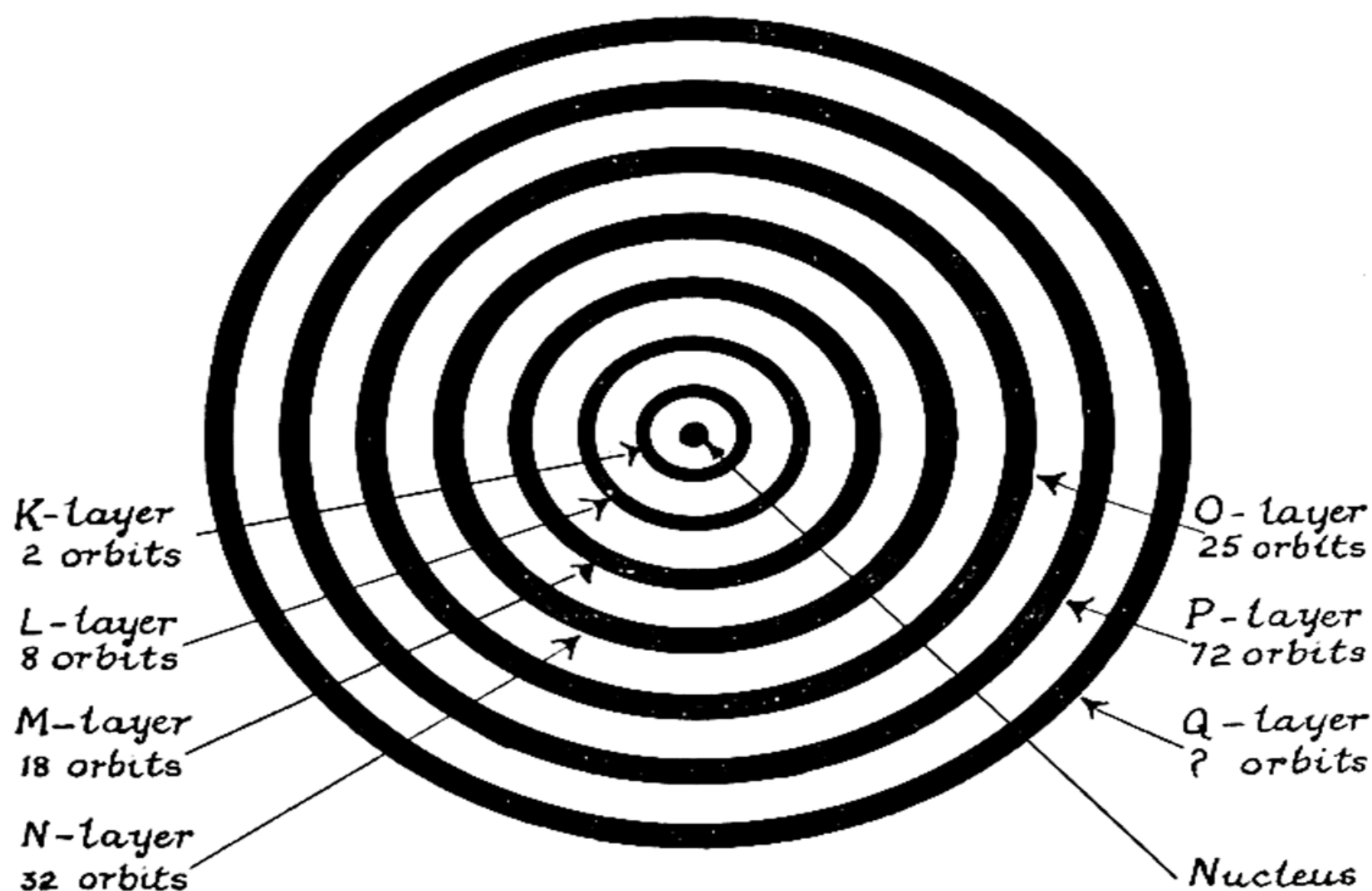


FIG. VIII.1. Bohr's conception of the possible electron orbits in an atom.

represents energy, whether you think of it as what has been paid to you for exercising energy or what, if you have it, you can pay to others to exercise energy on your behalf. The different seats in the theatre may thus correspond to the two-shilling, the three-shilling, the five-shilling, the seven-and-sixpenny, the half-guinea and the guinea energy-levels of the audience. There are no intermediate levels: you cannot by tendering six-and-three-pence obtain a seat rather better than one in the upper circle, but not quite so good as one in the dress circle. There are no seats intermediate between pit and upper

circle, upper circle and dress circle, dress circle and stalls, or stalls and boxes. The ticket that you buy admits you to one kind of seat and one only.

If you can afford only, say, a gallery seat and some kind friend, seeing you there, comes along and lends you the shilling necessary for a transfer from gallery to pit, you may move from an inferior to a better place. But the loan must be repaid. He lends you an exact amount: one shilling. You move to a more expensive (higher energy-level) seat and sometime, if you are a good citizen, the shilling must be returned to the lender.

But you cannot obtain even a cheap seat in the gallery unless there is one vacant; there is a definite limited number of gallery seats. Nor does your offer of an extra shilling automatically ensure your transfer to a better seat. It can do so only if one of the fixed number of better seats is unoccupied.

So with the electrons revolving round the nucleus of an atom. Corresponding to the most expensive seats with the best view of the stage, the orbits of the K-layer are those most closely bound to the nucleus by the strongest attractive energy. They are in the highest energy level. In this layer there are only two possible electron orbits; that is, no atom can have more than two K-layer electrons. The atom is unlike the theatre in that each one of the very best seats—the K- and L-layers—must be filled before seats in other parts of the house are made available to the queues at the doors.

The single electron of the hydrogen atom has normally an orbit in the K-layer. Only two orbits are available in this layer and these are filled by the two electrons of the helium atom. The atom of lithium has three electrons; two fill the available places in the K-layer and the third has an orbit in the L-layer. This layer has room for eight possible orbits. The atoms of beryllium, boron, carbon, nitrogen,

oxygen, flourine and neon, with atomic numbers of 4, 5, 6, 7, 8, 9 and 10 respectively and the same number of electrons, each fill up the K-layer to capacity with two electrons and then have more and more in the L-layer until it reaches its full complement of eight in the neon atom. Then with sodium (atomic number 11) an allocation to the M-layer begins. The process is quite orderly until argon (atomic number 18) is reached. After that we find that though the front seats, or orbits of highest energy level in each succeeding layer must be filled before others can be occupied, there can be electrons in the N-layer before the M-layer is quite filled; and so for the O, P and Q layers.

It must not be imagined that the orbits of electrons are necessarily circular. Each layer has certain possible circular orbits with the nucleus as centre. The rest are eccentric (actually, they are ellipses) and some of them are very eccentric indeed. It is important to realise that every orbit represents a definite, fixed path, just as every seat represents a definite fixed place in the theatre. An electron cannot make a slight change in its orbit any more than the playgoer can make a slight change in his seat. The spectator must always be in one particular section of the house. He may possibly move from the pit to the upper circle, or from the pit to the gallery; but there are no seats intermediate between pit and the upper circle, or between pit and gallery; he cannot find a half-way seat which is partly one and partly the other. Any move that he makes means an entire and clean-cut change of category between the seat that he leaves and the new one to which he goes.

In certain circumstances an electron may leave one orbit and occupy another. It cannot do so gradually, for there are no possible intermediate stages between one orbit and the next. It can, in a word, move only by a

sudden jump from one energy level to another. For that jump to take place exactly one quantum of energy is necessary. To make the electron jump from one orbit to another one quantum of energy must be lent to it; if, later, it returns by another jump to its original orbit, it repays the loan by giving out the same amount of energy.

An atom with all its electrons revolving in their normal orbits is said to be stationary. When energy applied from some outside source causes one or more electrons to jump to fresh orbits the atom is said to be excited. By placing a poker in the fire we feed heat energy into it. Its atoms absorb quanta of energy, which cause some of their electrons to make jumps to fresh orbits. Remove the poker from the fire and what happens? The electrons of the excited atoms jump back to their original orbits as the poker cools down. Each one in so doing repays one quantum of energy and so heat is emitted.

Since the energy per quantum is bound up, as we have seen, with the frequency, it follows that the frequency of the radiation depends upon the energy per quantum. Perhaps we can put that a little more simply. Planck showed that the energy in any quantum is to be found by multiplying the frequency by the number known as Planck's Constant: the higher the frequency, the greater the energy. The quantum is the unit of radiation and the greater its energy, the higher must be the frequency of the radiation concerned.

Quite a small amount of applied energy—a quantum of low frequency—may suffice to make an electron jump from one of the outer low-energy levels to another. When it makes its return jump the same small quantum is repaid and the radiation is heat of so low a frequency that it may be barely perceptible.

Now suppose that a blacksmith puts a piece of iron into his forge and continues to work the bellows until it is

white-hot. Quanta of energy of higher and higher value are put into the iron as the draught makes the temperature rise. Not just the outer electrons of the iron atoms, but some of the inner ones as well are made to jump to fresh orbits. When the piece of iron is withdrawn from the fire electrons at once begin to make their return jumps, each of which involves one quantum. Big quanta are concerned when electrons in the inner layers jump back; hence the radiation is of high frequency and our eyes detect it as bright light. Other return jumps between layers of lower energy-levels are also taking place at the same time. The quanta here are smaller and the radiation is at the lower frequencies which produce the sensation that we know as heat.

When we excite atoms by means of still larger quanta, as in the X-ray tube, we can cause electron jumps to take place which produce radiation of far higher frequency than that of visible light. To such radiation many forms of solid matter are transparent which are completely opaque to ordinary visible light. Quanta of yet higher values give rise in the processes of radio-activity to gamma rays, which have still greater penetrating power. Gamma rays, however, are not caused by jumps from energy-level to energy-level of orbiting electrons. They originate in the innermost part of the atom, the nucleus itself.

CHAPTER IX

Something about the Nucleus

THE READER MAY HAVE BEEN puzzled by one point in the brief description of the modern views of the make-up of the nucleus given in Chapter VII and by the arrangement shown diagrammatically in Fig. VII.2. We have seen that electrical charges of the same kind repel one another strongly. Protons are positively charged; therefore they must exercise violent mutual repulsion. Neutrons having no charge, exert neither electrical repulsion nor electrical attraction on each other or on particles which carry charges. In view of the enormous repulsive electrical force between protons and the fact that neutrons can do nothing to counteract it, how can two mutually repellent protons and two "inert" neutrons become tightly bound together and form a stable helium nucleus? We know that such a nucleus is stable, for to break it up we require the expenditure of the relatively very large amount of energy involved in a head on collision between a fast travelling helium nucleus and another nucleus.

For repulsion to exist between two similar electric charges they must be at not less than a certain distance from one another. This distance is very small indeed. So long as they are not less than this minimum distance apart particles with the same kind of electric charge repel one another; but if by some means they are brought closer together, strong attractive forces come into play which outweigh the electric repulsion and cause the particles to pack tightly together. Something of this kind must have happened to the atoms of matter in stars of the White Dwarf class, of which we spoke earlier. In these stars, as Jeans has shown, atoms must be stripped of all their

orbiting electrons right down to the K-layer. Thus only hydrogen and helium could possibly exist in balanced form. The atoms of all other elements must be positive ions. They have in some way been forced more closely together than the minimum distance at which electric repulsion can be effective. They are so tightly packed that White Dwarf matter is far denser and heavier than anything we know on earth; so dense, in fact, that a strong man could not lift a teaspoonful of it.

The further the investigations go, the more do they tend to confirm Prout's suggestion made in 1815 that the atom of hydrogen is the fundamental brick of which all matter may be built up, for, as we shall see later, a neutron is believed to be a proton which has absorbed an electron. There is, however, one difficulty which was for some time found very puzzling. It is this: if the nucleus of O_8^{16} (the commonest isotope of oxygen with a nucleus containing eight protons and eight neutrons) is taken as the standard, the unit of mass is one-sixteenth the weight of the oxygen nucleus. With one exception, all the isotopes of all the other elements have atomic masses consisting of a whole number of these units. But there is one exception—and that exception is hydrogen!

The commonest form of hydrogen has a nucleus consisting of just one proton; but it weighs a small amount more than one mass unit. Nor does the neutron, taken by itself, seem to fit into the picture properly. Taking the mass unit as one-sixteenth of O_8^{16} , the mass of the proton is 1.00758 and that of the neutron 1.00893; eight separate protons and eight separate neutrons weigh more than the same number of each welded into a nucleus of O_8^{16} :

$$\begin{array}{r}
 8 \times 1.00758 = 8.06064 \\
 8 \times 1.00893 = 8.07144 \\
 \hline
 16.13208 \text{ mass units}
 \end{array}$$

Here was indeed a problem! The solution was found by one of the most brilliant of the modern detectives of science, the great German mathematician, Einstein. Einstein put forward a theory which may at first seem utterly incredible. Matter and energy, he maintained, were different forms of the same thing. One could be converted into the other; in fact such a conversion must take place when a nucleus is built up from protons and neutrons. The energy needed to force protons so close together that attraction overcomes electric repulsion and to bind them and neutrons tightly together is provided by the conversion of some of their mass into energy.

In the oxygen atom the missing 0.13208 mass unit is not lost nor unaccounted for. It is represented by an exactly equivalent amount of binding energy. This astonishing discovery was summed up by Einstein in the delightfully simple form:

$$E=mc^2$$

E is the energy in ergs; m is the weight of matter in grammes and c is the speed of light, or 30,000,000,000 centimetres per second. The erg is a tiny unit of energy—13,560,000 ergs go to a foot-pound; but c^2 is a very large number, for it is 9×10^{20} , or nine hundred million million. If a gram (about one-thirtieth of an ounce) of matter, could it be converted entirely into energy, would suffice to provide many millions of the kilowatt-hours which our electric meters record as “units.” To build matter from the ultimate small bricks, or to make a simple nucleus, such as that of hydrogen, combine with another nucleus to form a third nucleus of greater weight and higher atomic number would require stupendous amounts of energy, which might be in the form of heat. The necessary temperatures exist inside the sun. It is believed that the building up of nuclei is going on continuously on a vast scale in the sun and the stars. One theory about

the heat and light that we receive from the sun is that they represent the energy released by the unceasing conversion of enormous amounts of hydrogen into helium.

Can the reader, I wonder, follow up the clues that have been given in this Chapter and find for himself the answer to the question: Why is hydrogen H_1^1 the only exception to the rule that if the mass of oxygen O_8^{16} is taken as sixteen units the mass of all other atoms is a whole number of units? It is worth his while to spend a moment or two in thinking out the reason, for by so doing he can discover whether or not he has grasped the principles of the relationship between mass and energy.

The answer is that in the hydrogen nucleus there is nothing but the single proton; there is no electric repulsion to be overcome, no packing to be done. Therefore no energy is expended; no mass is converted into energy and the proton retains the whole of its weight. In all other nuclei protons and neutrons convert a fraction of their mass into the energy required for the building of the nucleus.

Many other new clues are due to Einstein. His equations dealing with mass and energy, for example, leave no doubt that any piece of matter is heavier when it is in motion than when it is at rest. For the speeds of everyday life the increases in weight are so small that they can be neglected. The 80,000 ton *Queen Elizabeth* is only a fraction of an ounce heavier when travelling at twenty-five knots than she is when made fast to the quay. But when we come to speeds at all comparable with that of light the increases in weight become more and more important as the velocity approaches 300,000,000 metres per second. Electrons and other particles can acquire velocities of this order in the atomic laboratory and allowance must be made for the resulting increases in their weight.

A moving body possesses kinetic energy, which is

determined by its mass and its velocity. In atomic physics the units in which such energy is stated are not as a rule ergs, or foot-pounds. A unit called the "electron-volt" is found more convenient and as it is always cropping up in books and articles on the atom, or on the apparatus devised for dealing out rough treatment to the atom and its component parts, it may be useful to see what it means. An electric field (Fig. IX.1) is the region in which

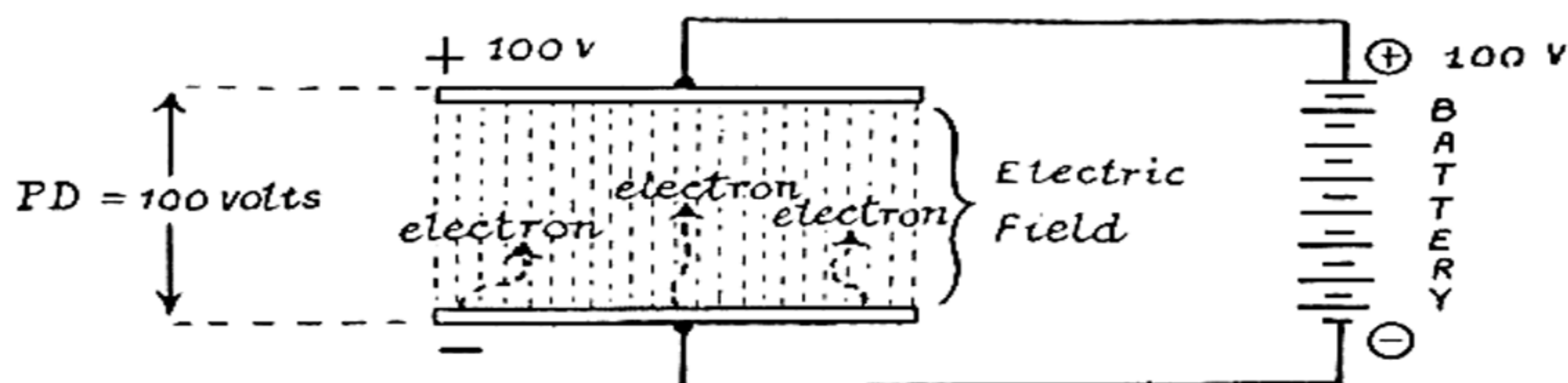


FIG. IX.1. Showing in diagrammatic form the electric field which exists between any two wires, plates or other conductors between which there is a potential difference, that is a difference of electrical pressure.

attractive forces exist between conductors carrying charges of different electric potential, or pressure. The unit of electric pressure is the volt. A potential difference (P.D.) of one volt is said to exist between conductors when one of them carries a charge which makes it one volt more positive than the other. In the familiar pocket flashlamp the potential difference across the filament of the bulb is about 3 volts; in our domestic electric lamps it is usually from two-hundred to two-hundred and thirty volts.

The electron, having a single negative charge, is strongly attracted by a positive charge. If the electron is free to move in the electric field, it moves towards the positively charged conductor; and the higher the positive charge on this conductor the greater the speed at which it travels through the field and therefore the greater its energy.

In a field in which there is a potential difference of one volt between the conductors the electron acquires a speed

which gives it an energy of one electron-volt, or 1 eV. In the valves of our wireless sets the electrons which enable broadcast transmissions to be detected, amplified and converted into sound waves have as a rule energies of 100 (battery set) to 350 (mains set) eV. The electrons which "paint" the images on the screens of our domestic television receivers have energies of 4,000–6,000 eV. Energy in the apparatus used in the atomic laboratory is measured usually in millions of electron-volts (MeV).

Einstein's views of matter and energy are completely confirmed by every test that we are able to make in the light of our present knowledge. They show that the old laws of the Conservation of Matter and the Conservation of Energy are no more than half-truths. It can no longer be held that an ounce of matter may change its form but must always remain an ounce of matter; nor must a million foot-pounds of energy always remain a million foot-pounds of energy of one kind or another. A single new conception replaces these two old ones. Mass and energy are different forms of the same thing, just as are water and steam. We can change some or all of the water into steam; but the total number of water molecules remains unaltered. Nor is it altered if the steam is reconverted into water. Einstein has shown that mass and energy are equally convertible and reconvertible without gain or loss. The new law replacing the two old ones is that of the Conservation of Mass-Energy. Starting with a given weight of matter, you can convert some or all of it into energy. But there is no destruction, for the energy so obtained is exactly equivalent to the weight of matter converted. We do not yet know how to change energy into matter; but it must be possible to do so and the law of the Conservation of Mass-Energy shows that the weight of matter produced in this way must be precisely equivalent to the amount of energy from which it is made.

CHAPTER X

Radio-activity

WE HAVE ALREADY SAID something about the stir caused amongst those engaged in pursuing the inquiry into the nature of matter by the discovery by the French scientists Becquerel and Pierre and Marie Curie that there were a few elements which behaved in a very strange way. Up till then the conception of an element had been that it was something composed of atoms, all of one particular kind, which never changed their essential nature, though they might become temporarily either positive or negative ions by the loss or gain of one or more orbiting electrons. But if an atom of oxygen, or zinc, or copper became ionised, it did not cease to be an atom of oxygen or zinc or copper. The elements, it was believed, were immutable. No matter how you treated the atoms of a pound of iron they remained iron atoms. They might combine with other atoms to form compounds; but from these compounds you could always recover, if you wished to do so, the individual atoms of which the original pound of iron was composed.

The discovery of the strange phenomenon of radio-activity, into which we must now go a little more deeply, showed that there were certain elements which spontaneously changed themselves into other elements by shooting away pieces of their nuclei. And, unlike the making and unmaking of chemical compounds, this was a one-way process. Nature had made certain kinds of nuclei able to break up of their own accord; but there appeared to be no way in which the fragments could be reassembled and bound together so as to rebuild the original nuclei.

At first only two radio-active elements were found: radium (No. 88 in the periodic table) and uranium (No. 92). Later it was discovered that all of the heaviest elements were radio-active and had no stable forms. These heavy elements are also those with the highest atomic numbers; that is, with the largest number of protons in their nuclei. Every element with a nucleus containing 84 or more protons or with an atomic weight of 210 and above must be of the self-destroying or radio-active kind. We know now that radio-active isotopes of most (and probably of all) elements can be manufactured in the atomic laboratory, if they do not exist in the natural state. There is even a radio-active isotope of hydrogen, the simplest and lightest element of all with a nucleus containing normally but a single proton. The exact reasons why an atom should be radio-active are not known with certainty, but radio-activity seems to occur most commonly in those nuclei in which there is a large difference between the number of protons and the number of neutrons. Both normal hydrogen H_1^1 and "heavy" hydrogen H_1^2 are stable. In the former the nucleus has one proton and no neutron; in the latter one of each. But the form of hydrogen H_1^3 , with two neutrons to one proton in the nucleus is unstable and breaks down by radio-activity.

Fig. X.1 shows all the known isotopes of the twenty lightest elements. It will be seen that all of these elements have at least one radio-active form. In most instances this is either a "light" or a "heavy" form of the element and there appears to be unbalance between protons and neutrons. In some cases though, there are both lighter and heavier stable isotopes and the reasons why there should be any sort of unbalance in the radio-active isotope are not apparent. Striking examples are S_{16}^{35} , Cl_{17}^{36} , A_{18}^{37} , K_{19}^{40} and Ca_{20}^{45} . In Fig. X.2 are seen the known isotopes of the thirteen heaviest elements up to plutonium, Pu_{94}^{239} ;

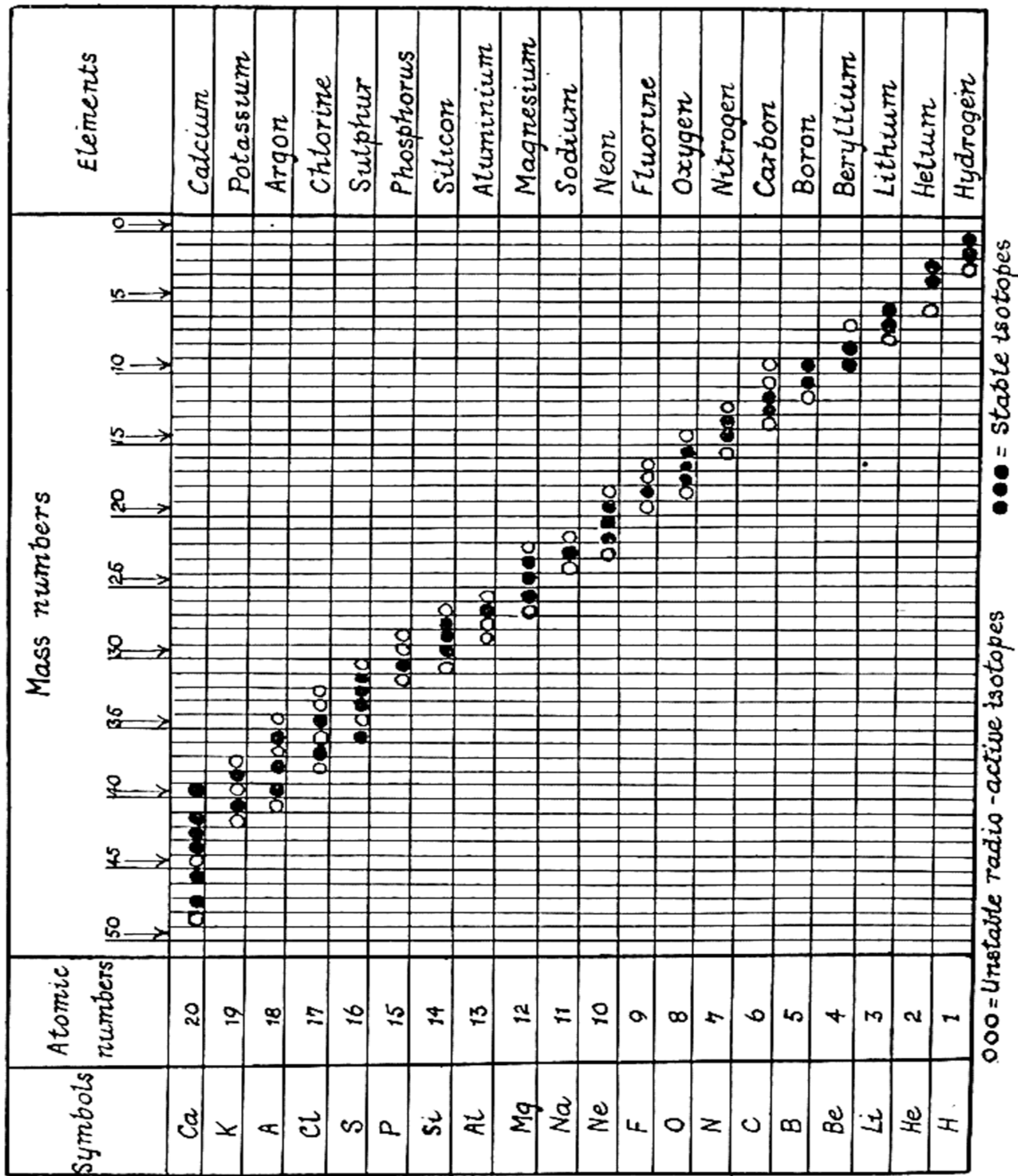


FIG. X.1. The known isotopes of the twenty lightest elements. It will be seen that none of these elements has less than three isotopes. Each of the twenty elements has at least one known radio-active isotope.

except for four stable isotopes of lead and one of bismuth, *all* are radio active.

Of the heavy elements which exist only in radio-active forms polonium has 84 protons and 126-134 neutrons; the still unidentified element No. 85 has 85 protons and

Symbols	Atomic numbers	Mass Numbers										Elements
		240	235	230	225	220	215	210	205			
Pu	94	o										Plutonium
Np	93	oo										Neptunium
U	92	ooo	oo									Uranium
Pa	91		oo	o								Protoactinium
Th	90		ooooooo									Thorium
Ac	89			oo								Actinium
Ra	88			o	ooo							Radium
—	87				o							—
Rn	86					ooo						Radon
—	85							o				—
Po	84						ooooooo					Polonium
Bi	83							ooooo	o			Bismuth
Pb	82							ooooooo	ooo	o		Lead

ooo----- Unstable radio-active isotopes

ooo----- Stable isotopes

FIG. X.2. Isotopes of the thirteen heaviest elements. Only two of these, bismuth and lead, have stable isotopes.

126 or more neutrons; radon has 86 protons and 133-136 neutrons; element No. 87 has 87 protons and 136 or more neutrons; radium has 88 protons and 135-140 neutrons; actinium, 89 protons and 138 or 139 neutrons; thorium, 90 protons and 137-144 neutrons; protoactinium, 90 protons and 140, 142 or 143 neutrons; uranium, 92 protons and 145, 146, 147, 149, 150 or 151 neutrons. Still heavier radio-active elements have been produced in the atomic laboratory and in the great atomic plants, though they do not occur naturally. These have from 93 (neptunium) to 96 (curium) protons and from 144 neutrons

upwards. Others will doubtless be produced and it is certain that in all of them a similar unbalance between the protons and the neutrons will be found. We may, perhaps, think of the nuclei of radio-active elements as being top-heavy and being unstable on that account.

It seems possible that in radio-active atoms the binding energy in the nucleus is insufficient to keep the assembly of protons and neutrons permanently welded together. In a piece of radio-active matter there is at any instant a certain number of atoms which are changing from their original form to something else by ejecting alpha or beta particles from nuclei. We do not know what determines the moment at which a particular atom undergoes the process of change by hurling out parts of its nucleus. All that we do know is that the rate of decay for any one radio-active isotope is fixed and immutable. This rate varies enormously from element to element and from isotope to isotope. In some cases half of the total number of atoms change their nature in a matter of millionths of a second; in others millions of years may elapse before the spontaneous conversion of half the atoms has taken place.

All radio-active substances, however, behave in the same way: for each a time can be found in which half the total number of atoms undergo nuclear changes. Suppose that we start with 8,192 atoms of a radio-active element about which we know that one half of the total number of atoms break down in one hour. The number is ridiculously small and would represent an almost infinitesimal quantity of the element. I have chosen it, partly because it is a number that is not beyond our imagination, but mainly because one can go on halving it.

At the end of the first hour, as Fig. X.3 shows, 4,096 atoms have broken down and 4,096 are left. At the end of the second hour half of these, or 2,048, have broken down and 2,048 remain. And so in each hour one half of

the available atoms are affected. At the end of the third hour 1,024 remain; at the end of the fourth, 512; at the end of the fifth, 256; at the end of the sixth, 128; at the end of the seventh, 64; at the end of the eighth, 32; at the end of the ninth, 16; at the end of the tenth, 8; at the end

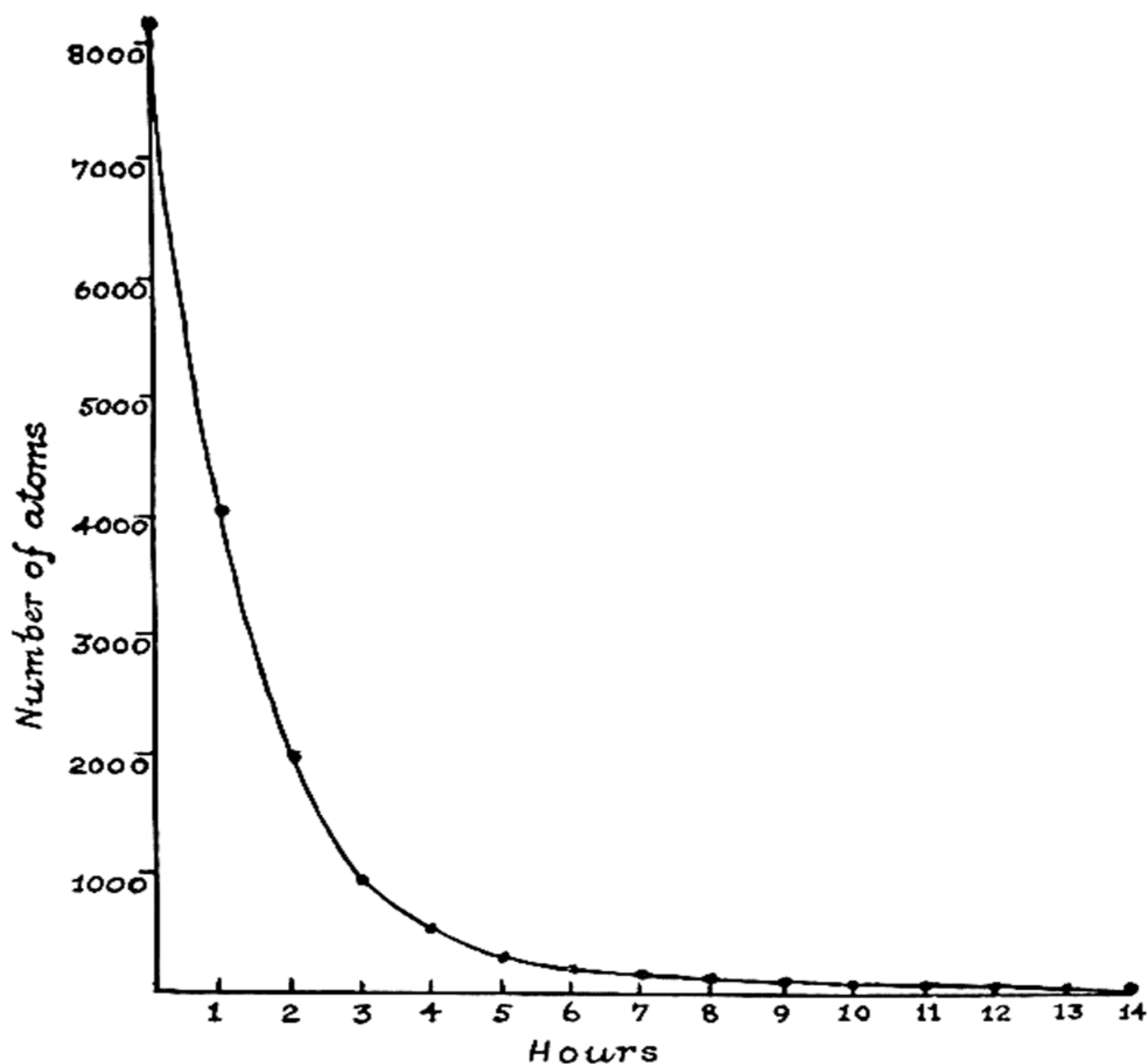


FIG. X.3. Typical curve of the rate of decay in a radio-active element. From this curve and from the explanation in the text the reasons for using the "half-life" of radio-active elements will be appreciated.

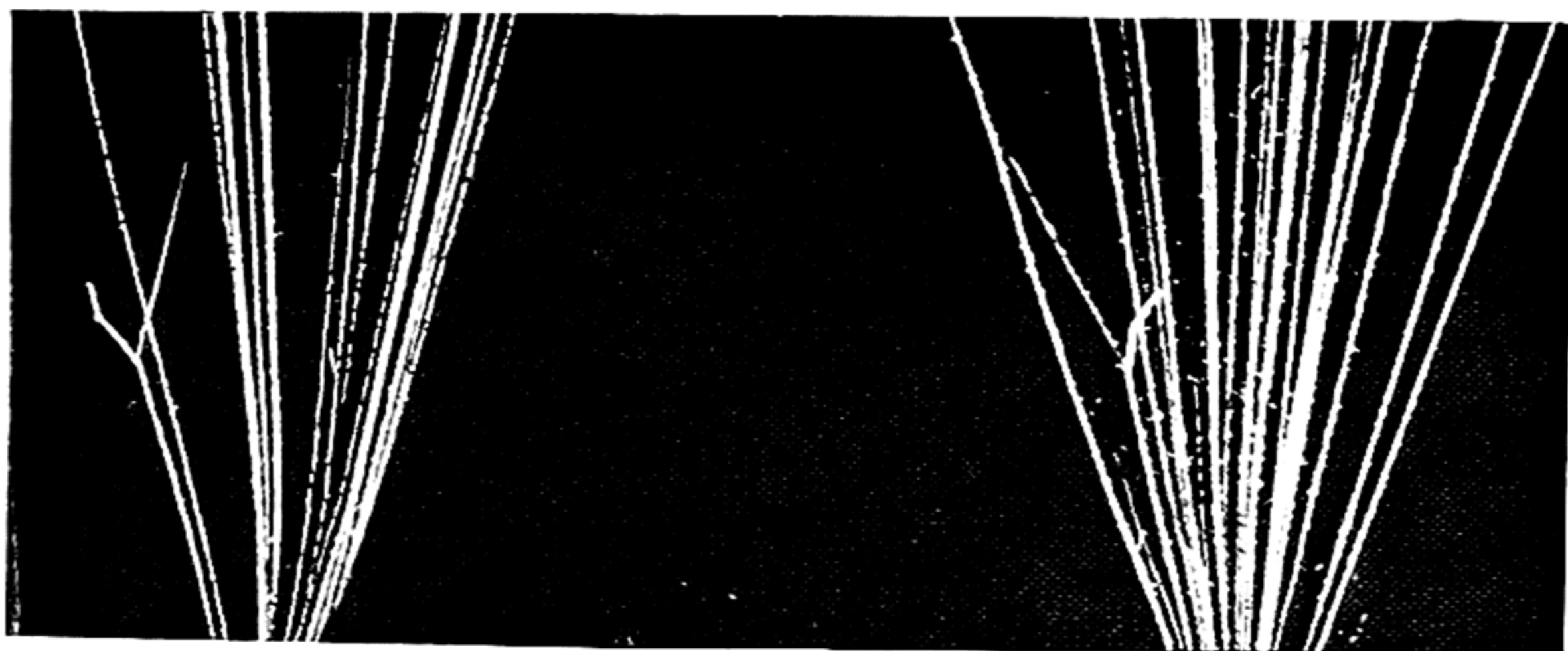
of the eleventh 4; at the end of the twelfth, 2; at the end of the thirteenth 1; at the end of the fourteenth hour the breakdown process is complete. Mathematicians will see that the rate of decay is exponential.

Now, though in this case the whole process takes fourteen

hours, one half of the total action takes place in the first hour. And this time is quite independent of the number of atoms with which we start: whether there are sixty, or six billion or sixty thousand quadrillion in a piece of radio active matter, one half of them will always break down in the half-life period. Every element has its own particular half-life, which never varies under natural conditions. Some idea of the enormous differences in the half-life periods of radio-active substances may be gathered from the following table showing a few of them.

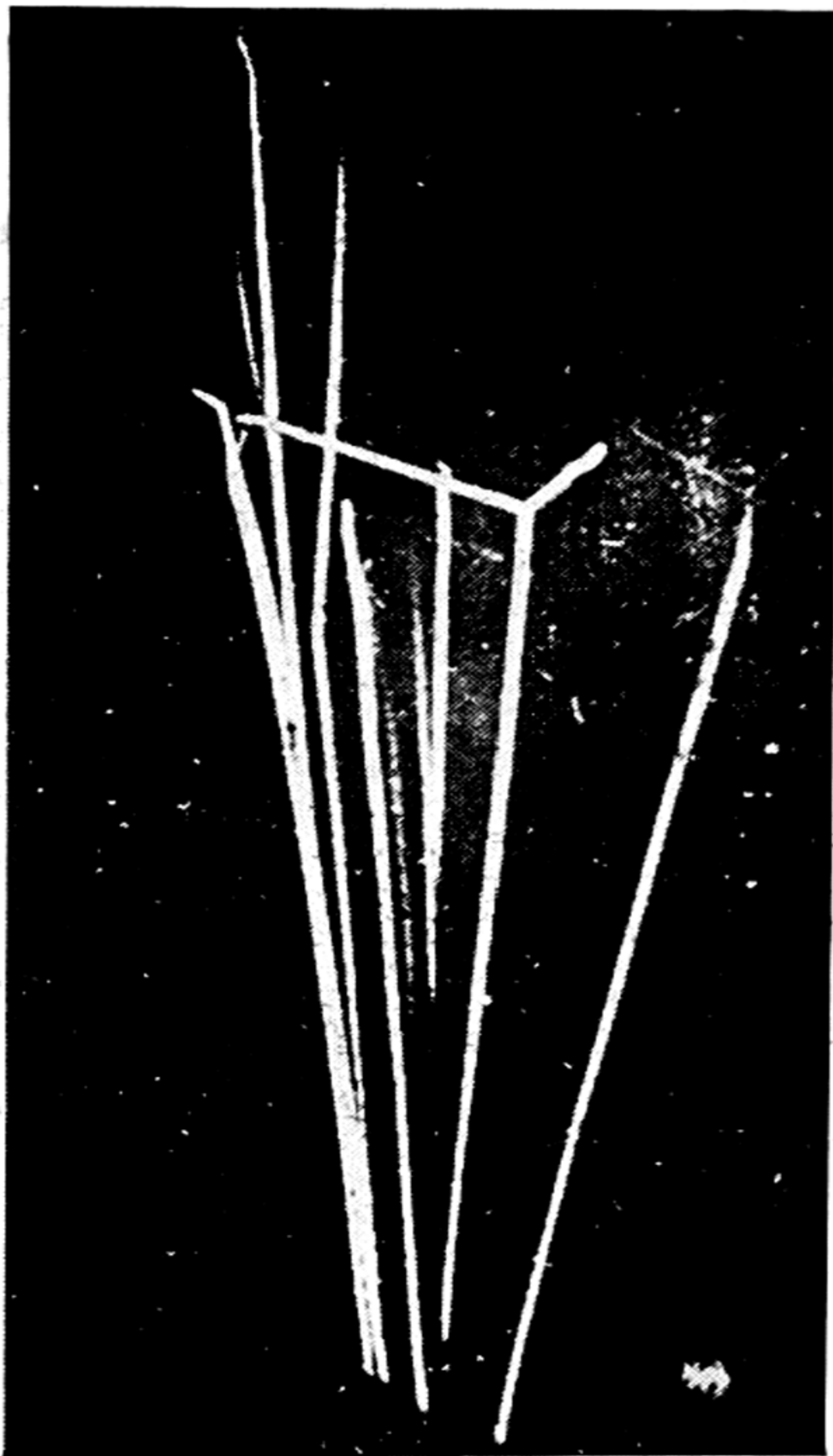
<i>Element</i>	<i>Isotope</i>	<i>Half-life Period</i>
Uranium	U_{92}^{239}	5×10^9 (5,000,000,000) years
Thorium	Th_{90}^{231}	1.4×10^{10} (14,000,000,000) years
Radium	Ra_{88}^{228}	6.7 years
Radium	Ra_{88}^{226}	1600 years
Radon	Rn_{86}^{222}	3.8 days
Lead	Pb_{82}^{214}	26.8 minutes
Polonium	Po_{84}^{212}	3×10^{-7} second (three ten-millionths of a second)

It may be wondered how even the wizards of the modern atomic physics laboratory can possibly determine such enormously long half-lives as those of U_{92}^{239} or Th_{90}^{231} ; the time cannot have been measured, for man has been in existence only a few million years and the atomic physicist is a very modern product. The short answer is that it was determined from observations of the decay of radio-active substances such as Ra_{88}^{228} and Rn_{86}^{222} that the process consisted of successive halvings in equal times. Once the time needed for any proportion of the atoms of a particular substance to break down had been accurately determined, the exponential laws of mathematics provided a ready means of fixing the half-life by calculation. To put it in another way, a mathematician given only a tiny but



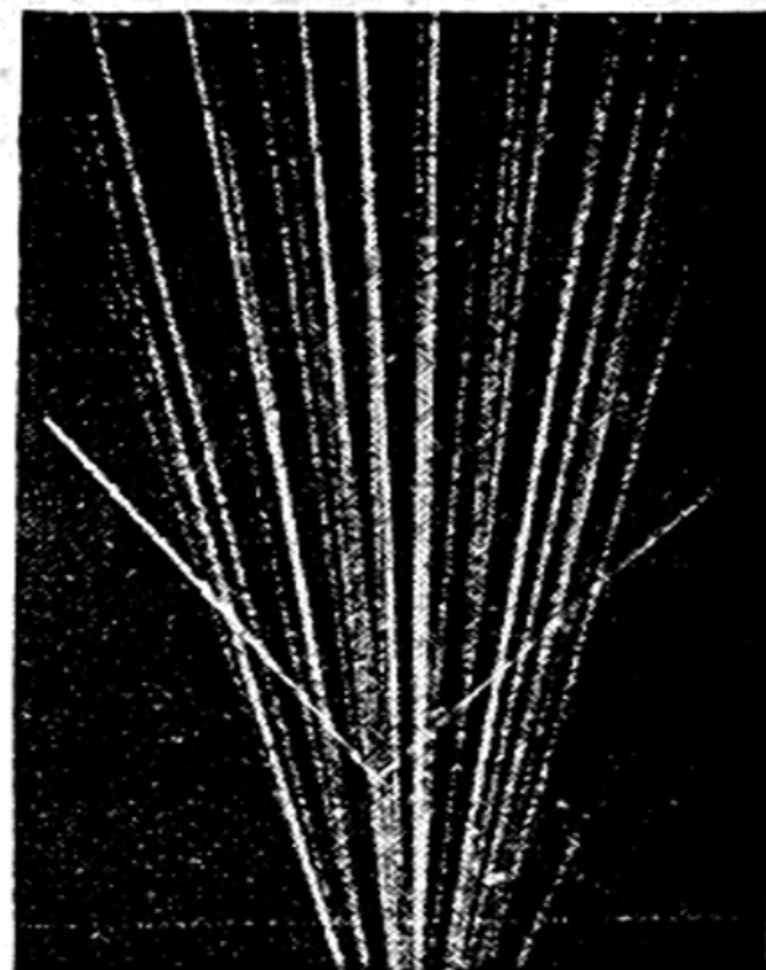
Cloud chamber photograph, showing the disruption of a nitrogen atom.

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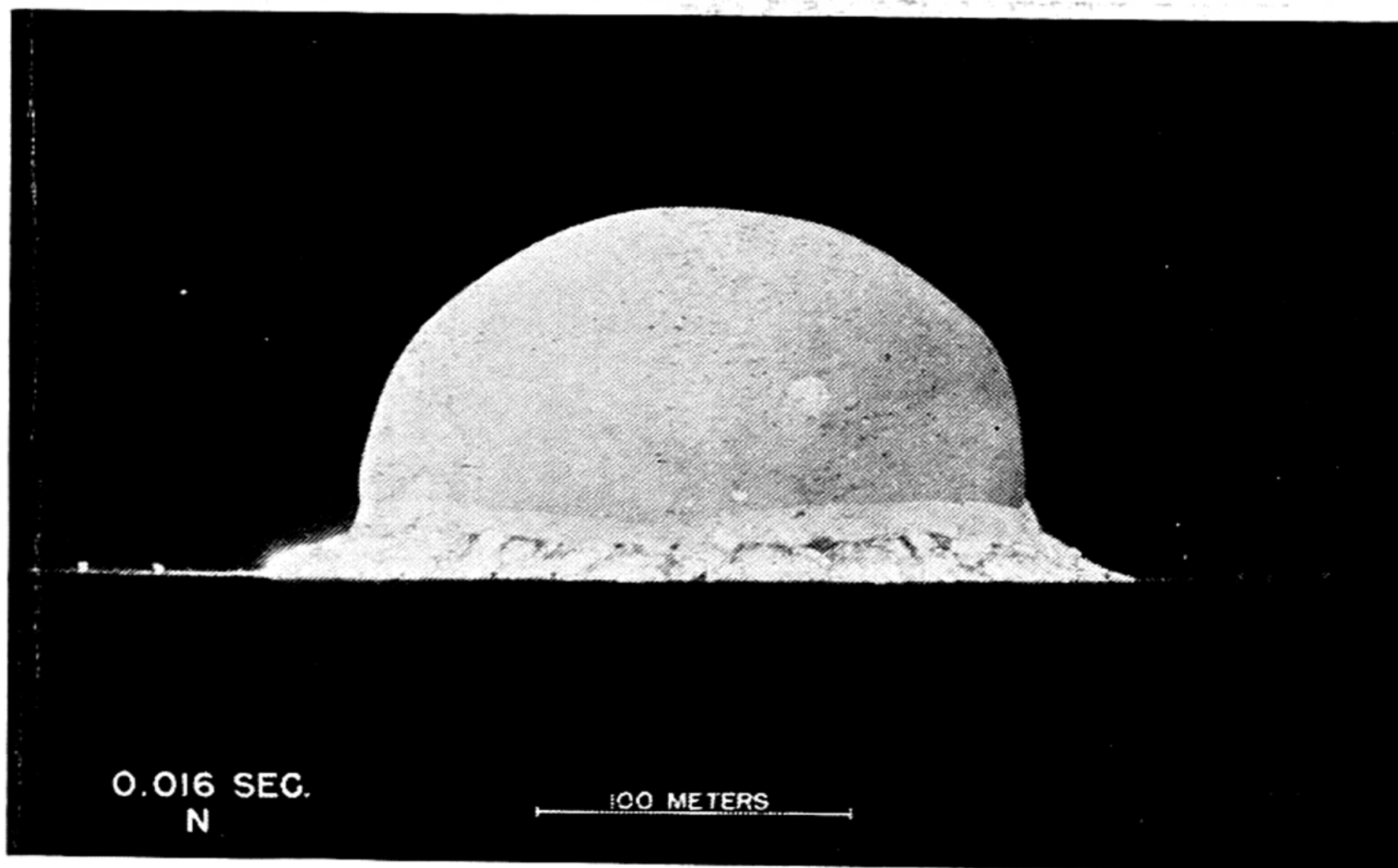
Cloud chamber photograph. The fork arises from a collision between an alpha particle and an oxygen atom.

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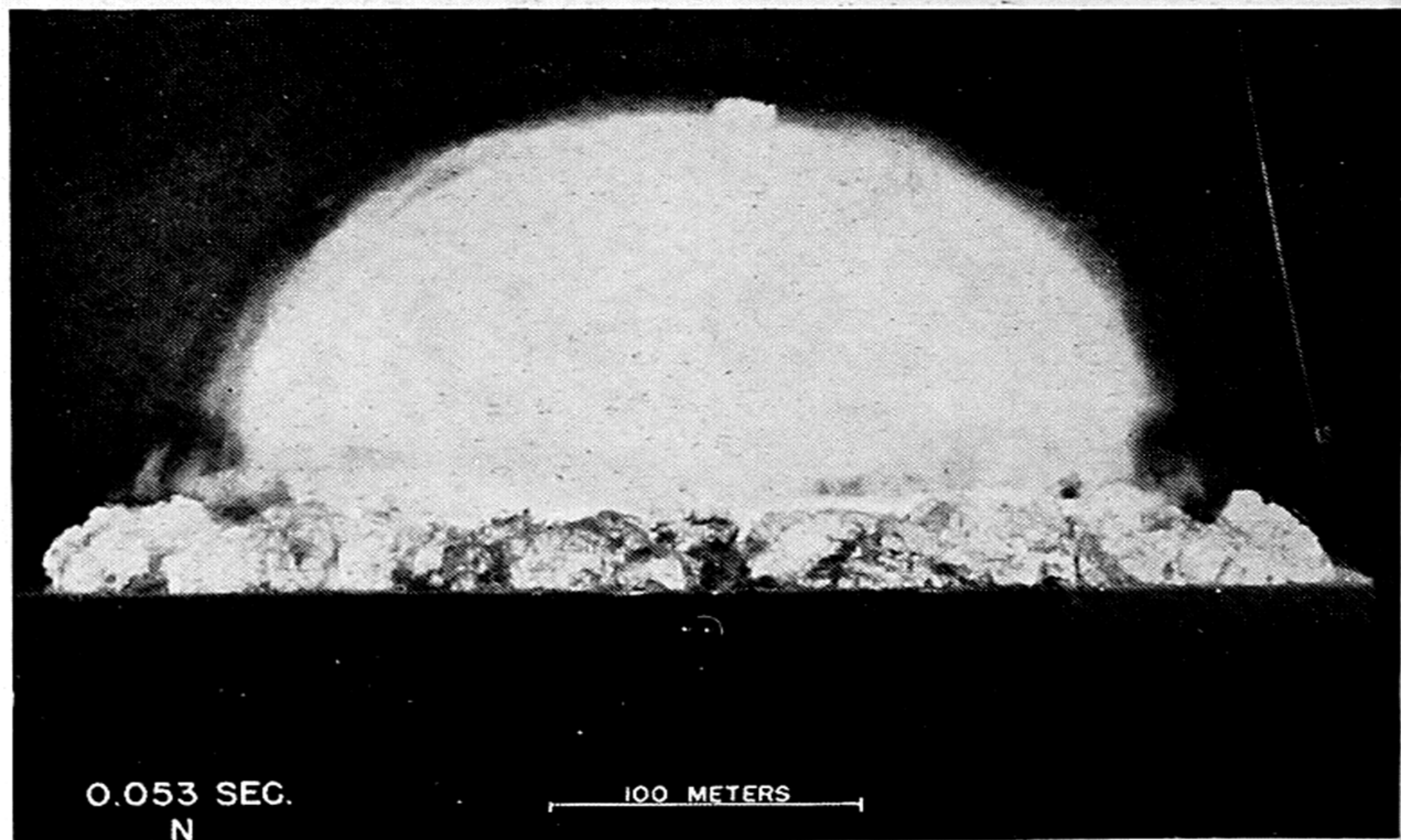


Cloud chamber photograph, showing the result of a collision between an alpha particle and a helium atom.

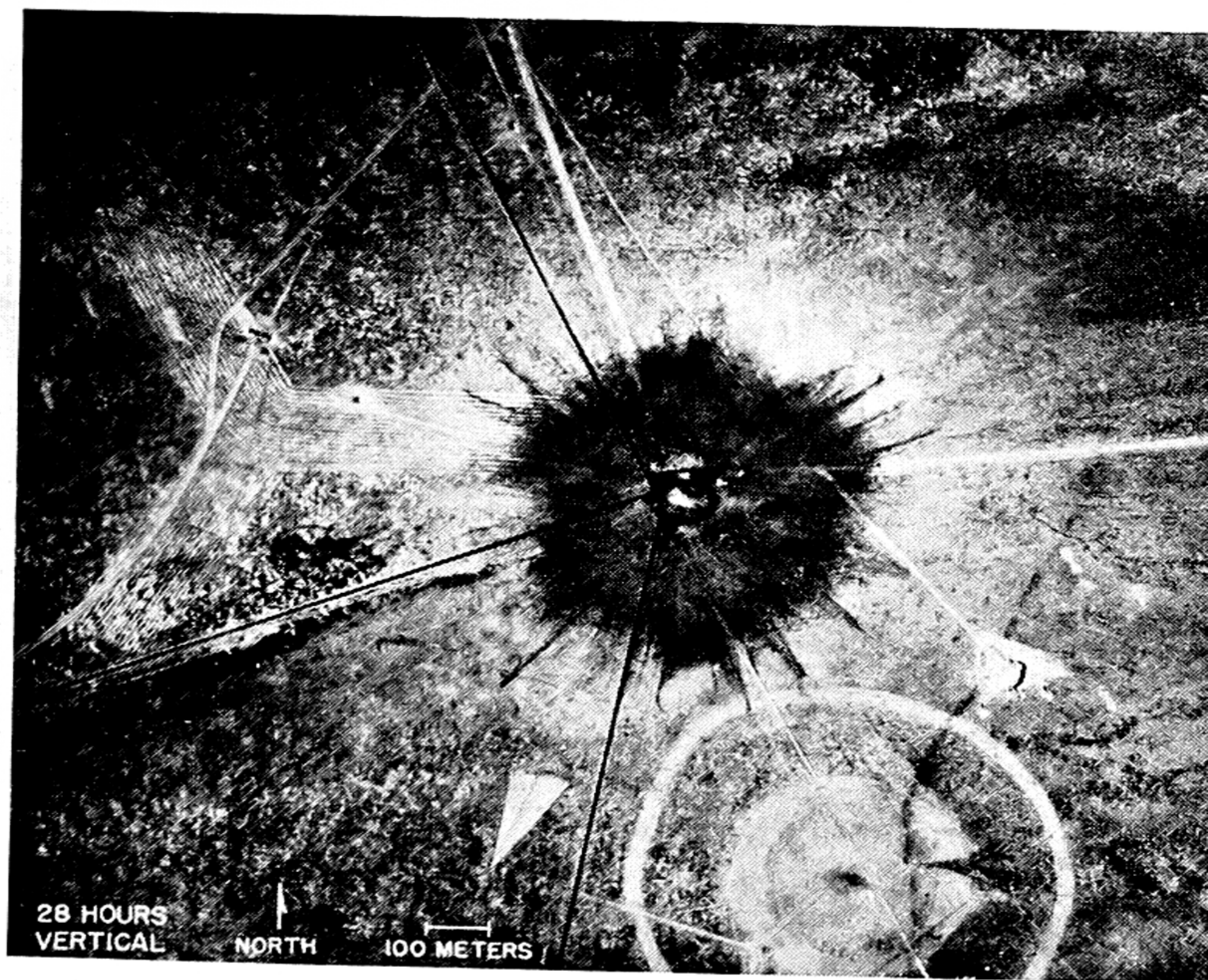
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The New Mexico atomic bomb explosion. 0.016 sec. after detonation.
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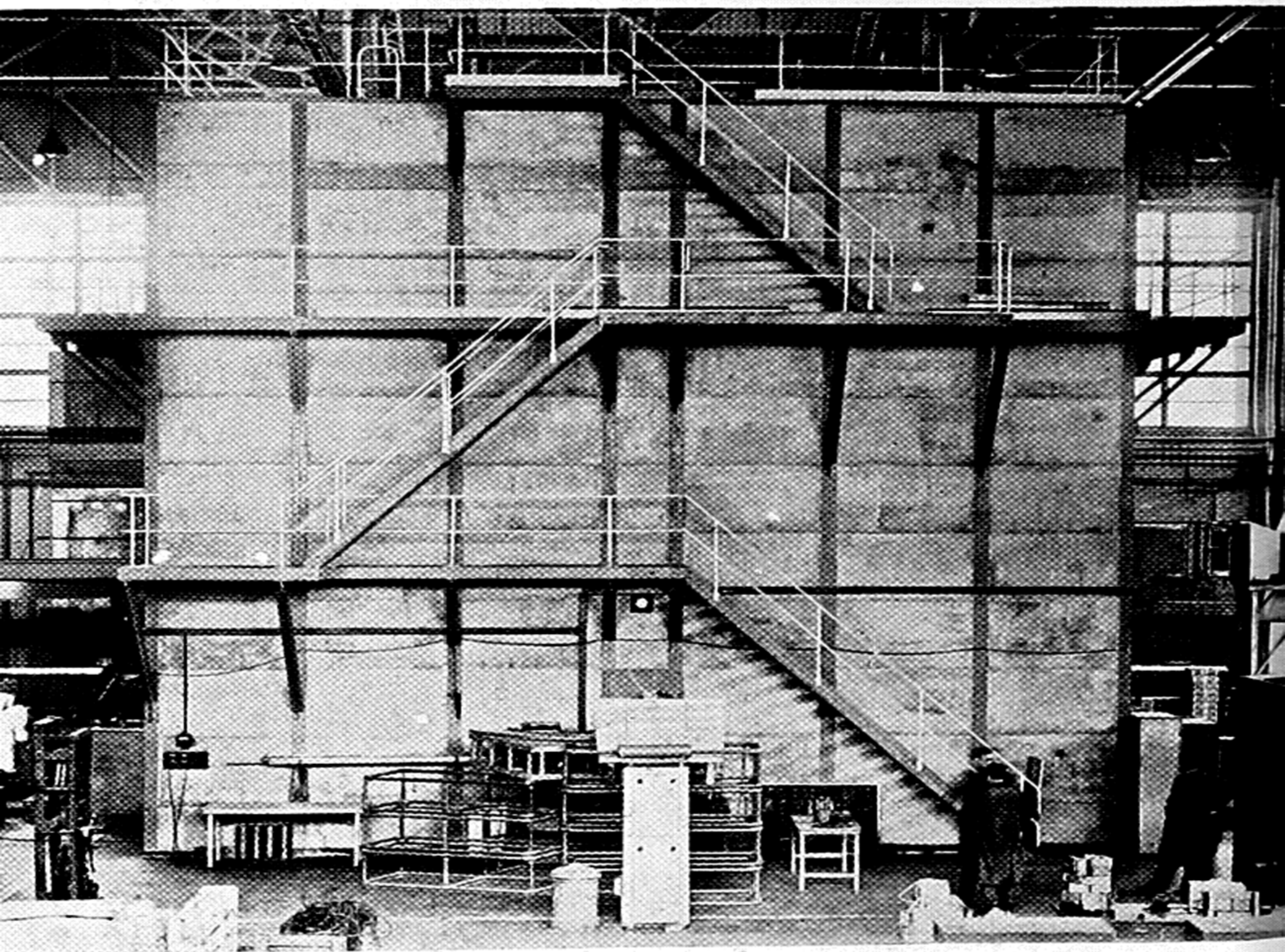


The New Mexico atomic bomb explosion. 0.053 sec. after detonation.
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Energy Commission.)



Aerial photograph of the site of the New Mexico atomic bomb explosion.
28 hours after detonation.

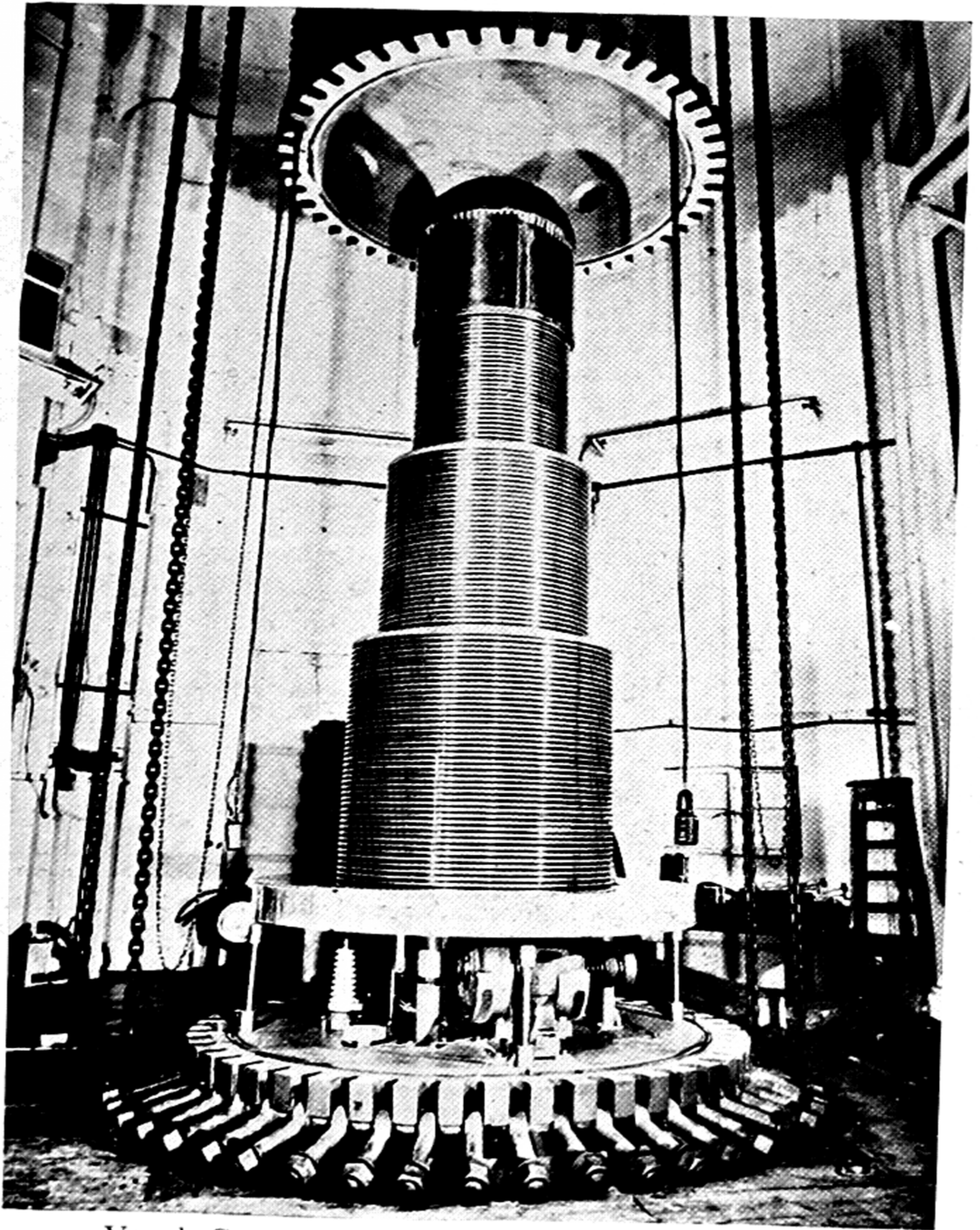
*(Reproduced by permission of the Ministry of Supply and the U.S. Atomic
Energy Commission.)*



General view of one face of 'Gleep'. A neutron spectrometer, in which neutrons from the pile are diffracted by a crystal, can be seen in the foreground.

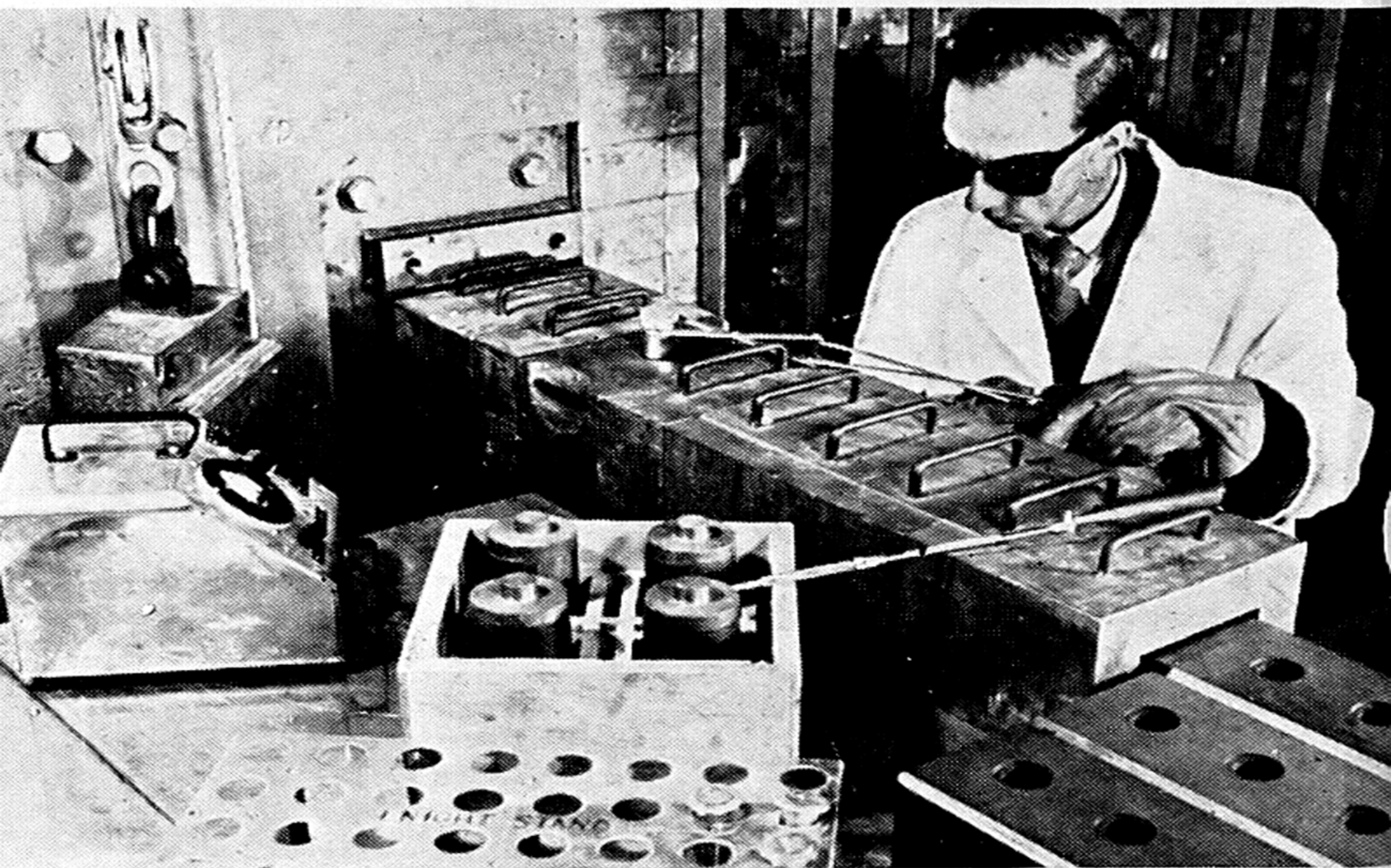
'Gleep': Graphite low energy experimental pile.

(Photo: Crown copyright reserved.)



Van de Graaf high voltage generator. When in use the machine is enclosed by the cover (top centre) which is filled with gas under pressure.

(Photo: Crown copyright reserved.)



The production of radio-active isotopes. A sample is being taken out after irradiation in 'Gleep'. The operator is protected from radiation from the material by the lead tunnel (shown with handles) through which the samples are taken with tongs. They are placed in the lead pots (centre) for transport.

(Photo: Crown copyright reserved.)

Mr Inder Krishen

B. Sg

Mr Inder Krishen

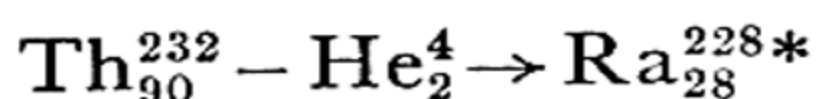
accurately drawn section of the curve in Fig. X.3, could identify the class of curves to which it belonged and could then make calculations which would enable him to fill in the complete curve. This is just what is done in fixing the half-lives of radio-active substances with very slow rates of decay.

Mathematical detective methods also work, so to speak, in reverse. Different kinds of lead are always found intermingled with deposits of radio-active metals such as radium, actinium and thorium. These leads are not radio-active. Radium is found associated with the lead isotope Pb_{82}^{206} , actinium with Pb_{82}^{207} and thorium with Pb_{82}^{208} . By comparing the proportion of the characteristic lead isotope present in samples of radium, actinium and thorium it is possible to calculate in each case how long the process of decay has been going on, or to work out the age of the Earth. The results of these calculations agree closely with others based on quite different data.

We saw in an earlier chapter that there are three different kinds of discards from the nucleus of a radio-active atom: alpha particles, beta particles and gamma rays. Alpha particles are now known to be helium nuclei, each containing two protons and two neutrons. Each contains four units of mass and two units of positive electrical charge and can be represented in shorthand either as α_2^4 or He_2^4 . In throwing out such a particle a nucleus loses four units of mass and therefore goes down four places in the scale of mass numbers. It loses also two units of positive charge and so goes down two places in the scale of atomic numbers. We have seen that the atomic number is the "identity card" of an element; hence the ejection of an alpha particle and the consequent reduction by two of its atomic numbers must mean a change in its nature.

To take one example, thorium $_{90}^{232}$ ejects an alpha
H

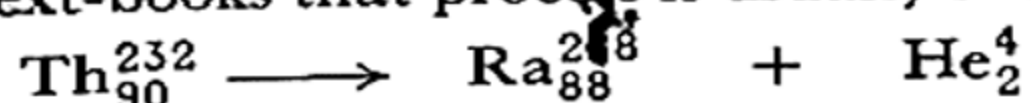
particle from its nucleus. Losing four units of mass, the nucleus reaches a new mass number of $232 - 4 = 228$. At the same time the positive charges are reduced by two: $90 - 2 = 88$. The result is a nucleus which for the moment we may call x_{88}^{228} . Referring to Fig. X.2, we find that the atomic number 88 shows that what was once thorium has now become radium and cannot be anything else. We can also verify from Fig. X.2 that radium has an isotope of mass number, or atomic weight 228. The new substance resulting from the shooting out of the alpha particle is therefore Ra_{88}^{228} . The process can be shown in the shorthand form:



A transmutation of elements has occurred, for thorium has been changed into radium; and a further reference to Fig. X.2 shows that there must be a sequel since the 228 isotope of radium is unstable and therefore cannot have a permanent existence in this form. Actually its half-life is 6.7 years. Ra_{88}^{228} breaks down in a quite different way. Its decay is an example of beta-particle ejection and the beta particle is an electron, one unit of negative charge. This electron, remember, comes from the nucleus itself and not from the swarm of orbiting electrons surrounding it.

But haven't we agreed that according to the latest theories the nucleus does not contain any electrons? How, then, can it possibly manage to eject an electron? What we saw was that there are no *free* electrons in the nucleus. It is believed that a neutron represents the fusion of an electron with a proton. A neutron is heavier than a proton and its extra weight can be accounted for by considering it as consisting of a proton plus an electron, plus the mass equivalent to the energy needed for the fusion.

* In scientific text-books that process is usually shown as:



In any case, electrons certainly are shot out by certain unstable nuclei and this view of the neutron would explain how such a thing could take place without there being any free electrons in a nucleus. The latest scientific belief is that the ejected electron comes not from the break-up of a proton but from the decay of a smaller particle, the meson, to which we shall come later. By discharging an electron the nucleus loses an amount of weight so small that it can be neglected and gains one unit of positive charge. Ra_{88}^{228} thus becomes x_{89}^{228} . Just what x is we can find from Fig. X.2. The atomic number 89 shows that it is some form of actinium. It is in fact Ac_{89}^{228} .

Another transmutation has occurred. It differs from that previously described in that the new element produced goes *up* one place in the series of atomic numbers, though its place in the series of mass numbers, or atomic weights, remains unchanged.

The emission of gamma rays causes no change in the weight or nature of the nucleus. This radiation represents the conversion of minute amounts of matter into the energy involved in the expulsion of alpha and beta particles.

In the earlier days of the investigation of radio-activity the nature of the substances resulting from the expulsion of alpha particles and beta particles was not at first realised. It was discovered, as we have seen, that the alpha particle was a helium nucleus and the beta particle an electron; but for some time it was thought that what remained of uranium, thorium, actinium, and radium atoms after these discards had been made still constituted forms of uranium, thorium, actinium and radium respectively. Not for some time was it grasped that after such a breakdown an atom completely changed its nature and belonged to an altogether different element. Hence, uranium, after it had discharged an alpha particle, was

taken for a new form of uranium and called UX₁. On discharging an electron UX₁ was held to change into UX₂. Similarly, ten kinds of radium, eleven of thorium and nine of actinium were catalogued and labelled. The old names are still used in many text-books and the non-scientific reader may find this very confusing, taking them for isotopes of the respective elements. Most of them are nothing of the kind. Uranium X₁ is in fact a form of thorium; Thorium X, a form of radium; Actinium A, a form of polonium; and Radium D, a form of lead! The following table will help to clear matters up, should the

PRODUCTS OF RADIO ACTIVITY		
<i>Old Term</i>	<i>Now recognised as</i>	<i>Isotope</i>
Uranium I	Uranium	U_{92}^{238}
Uranium X ₁	Thorium	Th_{90}^{234}
Uranium X ₂	Protoactinium	Pa_{91}^{234}
Uranium II	Uranium	U_{92}^{234}
Thorium 1	Radium	Ra_{88}^{228}
Thorium 2	Actinium	Ac_{89}^{228}
Radio-thorium	Thorium	Th_{90}^{228}
Thorium X	Radium	Ra_{88}^{224}
Thorium A	Polonium	Po_{84}^{216}
Thorium B	Lead	Pb_{82}^{212}
Thorium C	Bismuth	Bi_{83}^{212}
Thorium C I	Polonium	Po_{84}^{212}
Thorium C II	Thallium	Tl_{81}^{208}
Thorium D	Lead	Pb_{82}^{208}
Radio-actinium	Thorium	Th_{90}^{227}
Actinium X	Radium	Ra_{88}^{223}

PRODUCTS OF RADIO ACTIVITY		
<i>Old Term</i>	<i>Now recognised as</i>	<i>Isotope</i>
Actinium K	Element No. 87	Ac_{87}^{225}
Actinium A	Polonium	Po_{84}^{215}
Actinium B	Lead	Pb_{82}^{211}
Actinium C	Bismuth	Bi_{83}^{211}
Actinium C ₁	Polonium	Po_{84}^{211}
Actinium C ₂	Thallium	Tl_{81}^{207}
Actinium D	Lead	Pb_{82}^{207}
Radium A	Polonium	Po_{84}^{218}
Radium B	Lead	Pb_{82}^{214}
Radium C	Bismuth	Bi_{83}^{214}
Radium C ₁	Polonium	Po_{84}^{214}
Radium C ₂	Thallium	Tl_{81}^{210}
Radium D	Lead	Pb_{82}^{210}
Radium E	Bismuth	Bi_{83}^{210}
Radium F	Polonium	Po_{84}^{210}
Radium G	Lead	Pb_{82}^{206}
Radium Emanation	Radon	Ra_{86}^{222}

reader tackle a book dealing with radio-activity in which these terms are used.

The breakdown of these heavy radio-active elements into stable forms of lead is a complex process which takes place in many steps. In the typical case of the 238 isotope of uranium, illustrated diagrammatically in Figs. X.4 and X.5, there are no less than fourteen stages. The stage numbers in Figs. X.4 and X.5 are the same as those in the description now to be given and the reader

should have no difficulty in following the whole amazing process.

Stage 1. The uranium nucleus, containing 238 units of mass and 92 positive charges, ejects an alpha particle

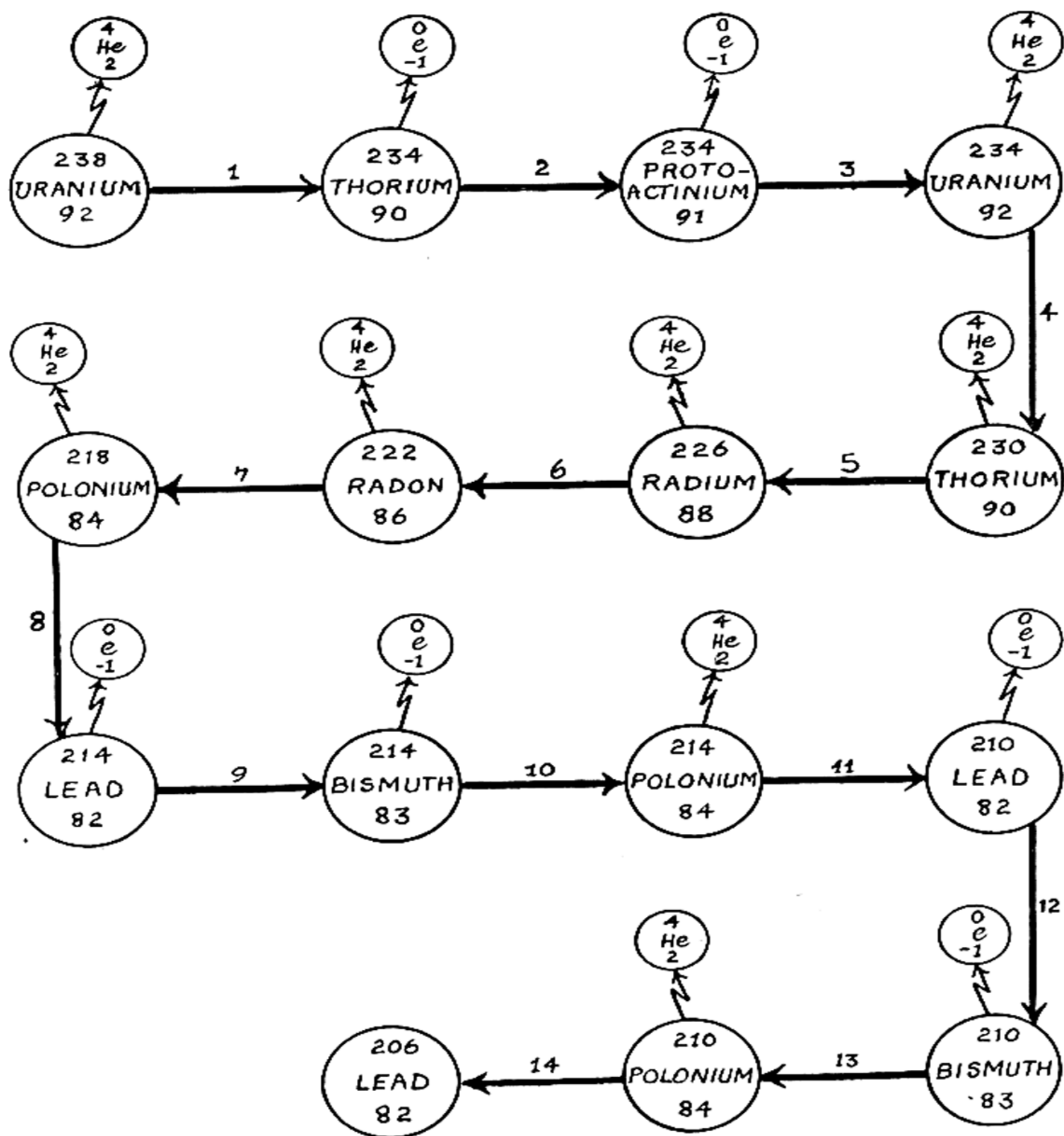


FIG. X.4. Diagram showing the fourteen stages of the radio-active change of uranium into lead.

with 4 mass units and 2 positive charges. Its mass becomes $238 - 4 = 234$ and its positive charges (atomic number) $92 - 2 = 90$. It has thus changed itself into thorium $_{90}^{234}$.

Stage 2. An electron is ejected. The mass remains unaltered at 234 units, but as it acquires one more

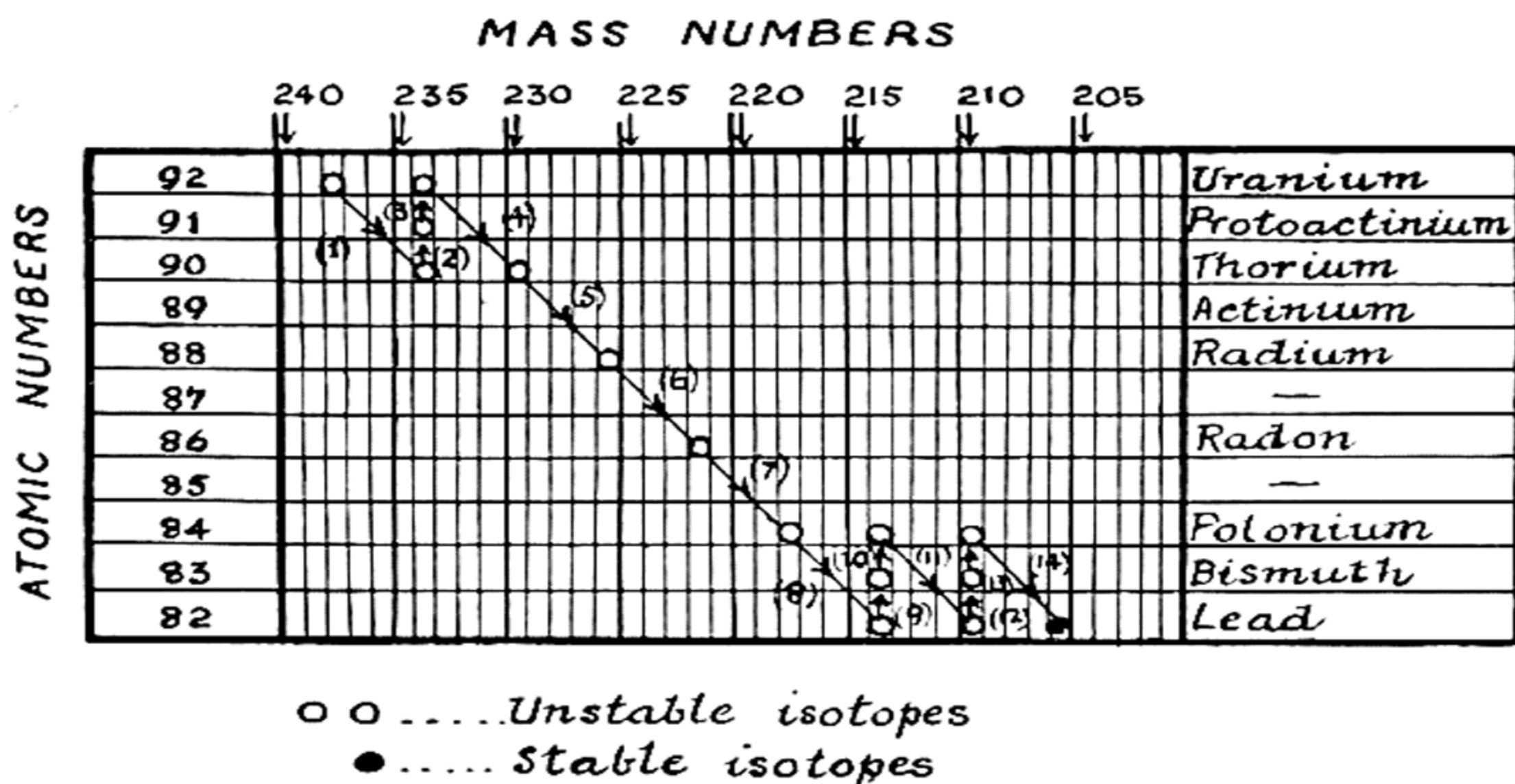


FIG. X.5. Graphical representation of the process illustrated in Fig. X.4. The stages bear the same numbers in both figures.

positive charge its atomic number goes up by one to 91. It has become protoactinium $_{91}^{234}$.

Stage 3. Again an electron is ejected and the atomic number changes to $91 + 1 = 92$. It has become uranium once more, but this is a different isotope— U_{92}^{234} —from the one with which we started.

Stage 4. Ejection of an alpha particle. The mass is now $234 - 4 = 230$ and the atomic number $92 - 2 = 90$. The nucleus has become thorium $_{90}^{230}$.

Stage 5. Ejection of an alpha particle. The mass is $230 - 4 = 226$, the atomic number $90 - 2 = 88$. Result: Radium $_{88}^{226}$.

Stage 6. Ejection of an alpha particle. Mass is $226 - 4 = 222$. Atomic number is $88 - 2 = 86$. Result: radon₈₆²²².

Stage 7. Ejection of an alpha particle. The mass is now 222 and the atomic number 84. Result: polonium₈₄²¹⁸.

Stage 8. Ejection of an alpha particle. The mass is now 214 and the atomic number 82. Uranium has become lead₈₂²¹⁴. But this is an unstable, or radio-active isotope and the process continues.

Stage 9. Ejection of an electron. The mass is unchanged, but the atomic number becomes 83. Result: bismuth₈₃²¹⁴.

Stage 10. Ejection of an electron. With the mass unchanged, the atomic number becomes 84. Result: polonium₈₄²¹⁴.

Stage 11. Ejection of an alpha particle. The mass is now 210 and the atomic number 82. Result: lead₈₂²¹⁰. Again uranium has become lead; but this is once more an unstable isotope.

Stage 12. Ejection of an electron. The mass is unaltered, but the atomic number becomes 83. Result: bismuth₈₃²¹⁰.

Stage 13. Ejection of an electron. The mass is unaltered and the atomic number becomes 84. Result: polonium₈₄²¹⁰.

Stage 14. Ejection of an alpha particle. The mass number becomes 206 and the atomic number 82. Result: lead₈₂²⁰⁶. This is a stable isotope of lead. There is no further radio-activity and the change is complete.

From Fig. X.5 it will be seen that the uranium nucleus in the course of its decay returns to its original atomic status at the end of *Stage 3* and then experiences a kind of landslide, being degraded in five successive stages, until at the end of *Stage 3* it first becomes lead. Twice it climbs back as far as atomic number 84; but each climb is

succeeded by a fall and the second of these causes it to become its third and final form of lead, the stable isotope Pb_{82}^{206} .

It is difficult to appreciate the genius, the skill, the toil and the patience which were needed for this and other complex series of radio-active transmutations to be first suspected and then verified by calculation and observation.

In 1922 C. D. Anderson (and almost simultaneously P. M. S. Blackett) observed some rather puzzling tracks in cloud-chamber photographs made in the course of investigation of cosmic radiation. The tracks were due to particles of the same mass as electrons. Were they electrons? Their behaviour when passing through electric and magnetic fields showed that they were not, for they were deflected in exactly the opposite direction. There was only one thing that they could be: they must be unit charges of positive electricity. Their existence has since been confirmed over and over again and they have received the name positrons. The positron is a particle, of the same size and weight as the electron, which carries one unit of positive charge.

It is not surprising that the positron eluded for many years the net cast by the scientific detectives. Anything which exists for a reasonable length of time should have been discovered by instruments of the delicacy of those available in the laboratory half a century ago. But what of a minute speck which seldom has an existence longer than about one hundred-millionth of a second? And that is roughly the life of the average positron, even if it escapes being attracted into and absorbed by the positively charged nucleus of another atom.

In any gas, or solid, or liquid there are at any instant numbers of free electrons—electrons, that is, which are temporarily detached from their orbits round the nuclei of atoms. Between a positron and each and every electron

there is an enormously strong attractive force. Thus the positron thrown out by an atom has no chance of having any but the briefest existence. It and an electron rush together. They collide and coalesce. Such is the force of the collision that the two tiny specks of matter are annihilated as matter and are transformed into pure energy. Each such collision results in one large quantum of energy; and, as we have seen, a large quantum means a high frequency of radiation. The result here is the complete transformation of two minute pieces of matter into a "whiff" of gamma-ray radiation.

CHAPTER XI

From the Depths of Outer Space

DURING THE GREATER PART of the nineteenth century Scientists had tried from time to time to solve one problem in electricity for which no really satisfactory explanation could be found. At first sight it may not seem to be a particularly important problem, but it has since turned out to be one of very considerable moment. The problem is simply this: if two metal plates are given opposite electric charges and insulated from one another in what appears to be a perfect manner, the charges gradually leak away, no matter what precautions we take. In the light of modern knowledge "charging" means that on one of the plates (the negative) there is a surplus of electrons, whilst on the other (the positive) there is an electron deficiency. In some way surplus electrons must leak away from the negative plate and electrons must travel to the positive plate to make up the original deficiency there.

Now a flow of electrons from one place to another constitutes what we call an electric current: the denser the stream of electrons, the heavier the current. Electrons can flock to a place only if there are protons or positive ions to pull them by the force of electric attraction. And free electrons, free protons and positive ions can exist only in a substance—gas, liquid or solid—that is ionised; a substance, that is, in which some atoms or molecules have temporarily either lost or gained an electron and so have become positive or negative ions.

There can be no flow of electrons, and therefore no electric current, without ionisation.

From the electrical point of view all substances can be divided into two great classes: conductors and insulators. Conductors are those substances through which an electric current can pass. Almost all good conductors are metals, silver and copper being the best of all. Silver is too expensive to be widely used and copper is the metal generally employed to provide long-distance paths for current from generating stations to our homes and short-distance paths inside these homes. Insulators are, in theory at any rate, substances which present a complete barrier to the passage of electric current. In practice they are substances through which only currents so small as to be virtually negligible can flow. The division between conductors and insulators is not quite hard and fast. There are good conductors, fairly good conductors and bad conductors. Similarly there are good, fairly good and bad insulators. The good conductor may be regarded as a supremely bad insulator and the good insulator as a conductor of outstanding poorness. There are no perfect conductors under ordinary conditions, for all offer some opposition, or resistance, to the passage of current. Nor are there any perfect insulators, since the best allow minute amounts of current to flow through them.

Fig. XI.1 shows diagrammatically the conditions normally prevailing in such a good conductor as a length of copper wire. Notice carefully that the drawings *are* diagrammatic: each copper atom has in reality twenty-nine orbiting electrons but only the outermost ones are shown, for only in the outer ring are there electrons which are easily detachable. In a piece of copper the atoms are so tightly packed that when outer electrons are in the positions marked x in Fig. XI.1 they are just about equally attracted by two different nuclei and therefore hardly know, so to speak, to which atoms they belong. The result is that outer electrons are

continually jumping from one atom to another. This means that at any moment some copper atoms are positive ions and others negative ions. In other words, a length of copper wire is continually ionised.

Imagine now what happens when a single electron, provided by a battery or other source of current, enters a wire. It is immediately attracted by an atom which has become a positive ion and takes the place of the electron which this atom had lost. Previously the wire contained

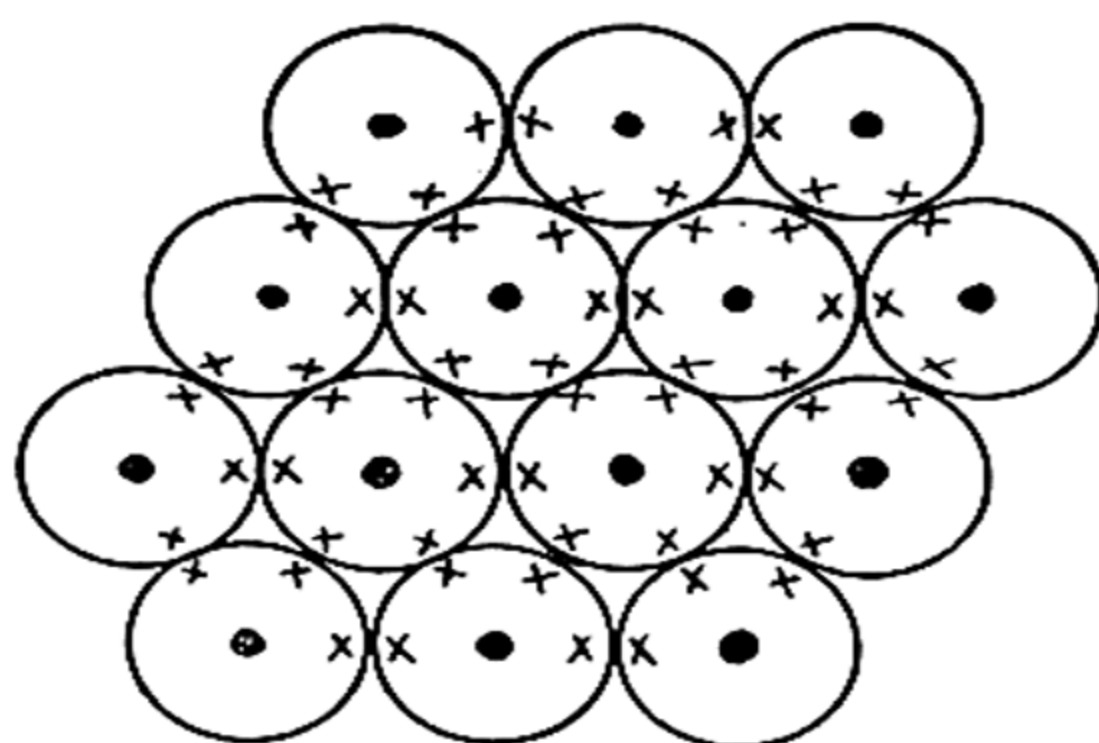


FIG. XI.1. Diagrammatic view of atoms in a piece of copper wire. Outer-ring electrons when in the positions marked *xx* are almost equally strongly attracted by two nuclei. There is thus an electron exchange between atoms, which means that at any instant many of these atoms are positive or negative ions.

at any instant just as many free electrons as positive ions. Any atom becoming a positive ion was neutralised an instant later by an electron from another atom. But with the entry of the newcomer there is one electron too many. And so electron exchanges between atoms take place right down the length of the wire. There is always one surplus electron and this issues from the far end of the wire. One electron goes into the permanently ionised conductor and one—not necessarily, or even probably the same electron—comes out at the far end. For “one electron” read “several million million million electrons” and you have some idea of what takes place in a wire when quite

a small electric current is flowing. Every time you press the switch of your pocket flashlamp you allow about 2×10^{18} —two trillion electrons—to flow in this way from the battery through the filament of the bulb in each second.

Dry air is an almost perfect insulator, for the molecules of its gases are normally un-ionised; nor can they be ionised without the expenditure of large amounts of energy. Yet, as has been mentioned, electric charges on metal plates surrounded by dry air leak away. They can do so only by receiving or losing electrons. Any flow of electrons constitutes an electric current and this can occur only if there is ionisation. *Something*, then, must supply the energy needed to ionise the air insulation. This leaking away of charges had been observed long before the existence of the electron or the process of ionisation were discovered. The new discoveries did not in themselves provide any clue to the solution of this particular mystery. At first, in fact, they seemed to make it even more mysterious.

Then came an amazing development. It was found that from somewhere in the depths of space the earth was continually receiving showers of energy of a kind entirely different from the light and the heat furnished by the sun. This energy is conveyed by particles—mainly protons—reaching us at enormous velocity from the depths of outer space. It has been named cosmic radiation, or cosmic rays. Only a very small amount of the protons forming “primary” cosmic radiation reaches the surface of the Earth, for the greater part of them are dispersed by collisions with particles in the atmosphere.

At ground level few, if any, of the original particles from space reach us. But, by colliding violently with atoms of the gases in the upper air, these primary cosmic particles give rise to certain by-products of a startling kind

which do reach us. These by-products are also particles of great velocity and energy. Such is their penetrating power that their arrival has been recorded hundreds of feet under water and even in the galleries of deep mines. One important cosmic-ray research centre operates in the Holborn tube station in London; fast-travelling particles due to the action of cosmic rays have no difficulty in penetrating the thick mass of soil above the station.

It has been established beyond all doubt that cosmic radiation is responsible for the small degree of ionisation which turns the otherwise perfect insulator, dry air, into a partial conductor and allows electric charges to leak away. The energy needed to bring this about is very great but the by-products of cosmic rays have no difficulty in supplying it.

It has been mentioned that the effects of cosmic rays led to the identification of a new particle of matter, the positron. They led also to the discovery of a still more puzzling new particle. In cloud-chamber photographs tracks were observed from time to time which did not fit in with the behaviour of electrons, positrons, neutrons or protons. They indicated fast-moving bodies much heavier than electrons or positrons, but a great deal lighter than neutrons or protons. Vast numbers of observations and calculations made in many different countries proved that these particles were of two broad kinds. Some had about 200 times the mass of an electron; some, about 300 times that mass. In a word, they were *intermediate* between the electron and the positron on the one hand and the proton and the neutron on the other. Hence they have been given the name "mesons" from the Greek word "mesos," meaning intermediate, or in between. The same word forms the first two syllables of Mesopotamia, the Land between the Rivers. Scientists, unfortunately, are apt to have little respect for ancient tongues; some of them have

elected to pronounce "meson" so as to rhyme with "reason," though it would be more correct to make it rhyme with "lesson." Even scientists don't talk of "Meezopotamia"!

What the meson is is still something of a mystery. Sometime before its existence had been confirmed the Japanese physicist Yukawa had announced his conclusion that the make-up of the nucleus could not be explained satisfactorily by regarding it as a collection of protons and neutrons, bound together by an enormous attractive force which overrides electric repulsion between particles of similar charge if the distance between them is small enough. Something else was needed. This may be described as "chunks of solidified energy"—we have already seen that energy may be converted into matter and *vice versa*. The mass of the meson corresponds to that of the chunks of solidified energy that his calculations required. The meson may, then, represent the appearance in the form of a small particle of matter of the energy released when certain kinds of nuclear break-up are produced by collisions.

One thing is certain. Mesons themselves cannot come to us from sources in outer space. Any particle reaching us from such sources must have been travelling for hundreds, thousands, or even millions of years; but the life of a meson is found to be very short. After a brief existence it disintegrates. In addition to those due to cosmic rays, mesons have now been produced in the laboratory by head-on collisions at very high speeds.

It is believed that the cosmic-ray mesons, whose arrival is observed on, above and below the surface of the Earth, are brought into being in two stages. Collisions in the upper regions of our atmosphere between high-velocity particles from outer space and the nuclei of atoms of gas result in the production of "primary" mesons of high

velocity and energy. Most of these disintegrate far above the surface of the Earth. For a small proportion, though, the rest of the story is different. These live long enough to travel a considerable distance earthwards through the atmosphere. Eventually they collide with nuclei and produce the "secondary" mesons which make up a large part of the cosmic radiation recorded by our instruments.

Recent discoveries have added yet another to the number of different kinds of bricks of which matter is made. This is the neutrino, which has the same mass as electron and positron, but no electric charge whatever. The single brick of Democritus was divided by Thomson and Rutherford into protons and electrons. To-day the heavyweight particles known are two: the proton and the neutron. The two kinds of meson form the medium-weights and there are three lightweights, the electron, the positron and the neutrino. Shall we find one day that neither the proton nor the neutron is an indivisible unit? Is it possible that each is in some way a conglomeration of electrons, positrons, neutrinos—and energy? Will particles smaller still be found?

Small fleas have lesser fleas

On their backs to bite 'em.

These lesser fleas have smaller fleas . . .

And so *ad infinitum*.

CHAPTER XII

Chain Reactions (I)

RUTHERFORD WAS ALWAYS sceptical about the possibility of harnessing the huge amounts of energy contained in the nuclei of atoms. He had no doubt that the energy was there; but all of his experiments had appeared to show that it could not be released without the use of still greater amounts of energy. To take a simple analogy, we can think of a small-holder who owns a donkey and a cart and is faced with the task of moving his potato crop to a place where it can be stored safely until required. The donkey, though strong and easily able to draw the cart, is both lazy and obstinate. So much so that our imaginary small-holder finds that the energy expended in adjuring and belabouring the animal and pulling its bridle is more than he would put out by using a wheelbarrow and his own strength to shift the potatoes. It isn't worth while to use the donkey.

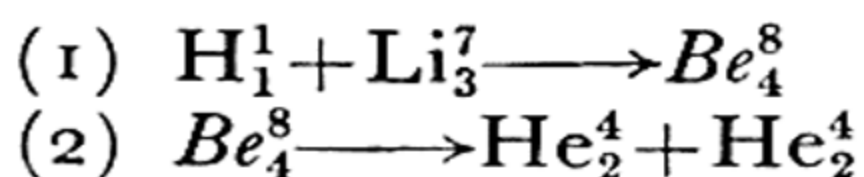
And to Rutherford it seemed that the vast store of energy within the nucleus might need so great an expenditure to release it that the game would not be worth the candle. He was too great and too experienced a scientist to declare positively that man would never be able to make use of this energy; his attitude was that, so far as he could see and so far as his experiments had gone, any such thing appeared to be unlikely.

In view of the results obtained by him, by his laboratory teams and by physicists in many parts of the world this attitude is entirely understandable. The early experiments consisted, as we have seen, in bombarding the nuclei of atoms of different kinds with alpha particles. If a direct

hit was made, a large amount of energy was released; but since the odds against such a hit are more than a million to one, the great majority of the bullets fired produced no result at all. The *output* energy from the direct hits was in fact much less than the total *input* energy of the alpha particles.

For later experiments Rutherford felt the need for denser volleys of faster flying bullets. Cockcroft and Walton provided what he asked for by devising a method, still in use, of producing artificially streams of particles far more copious and more highly energised than those ejected by radio-active materials. Their method was to devise a means of increasing electrical pressure, or voltage, to new high figures.* By means of their apparatus intense electric fields were produced. The projectiles first used were protons and energies of some 400,000 electron-volts could be imparted to these.

With the Cockcroft and Walton apparatus bombardments of lithium nuclei by protons brought about the first artificially produced transmutation of elements: those previously obtained had been due to the natural process of alpha-particle ejection by radio-active substances. The result of this historic experiment was found to be as follows: a proton with one unit of mass and one positive charge, struck a lithium nucleus, with seven mass units and three positive charges; for a brief instant the mass units and the positive charges combined to form one nucleus with eight mass units and four positive charges—an unstable isotope of beryllium; then this broke apart into two stable helium nuclei, each with four mass units and two positive charges. In shorthand form the processes are:



* For a description of the apparatus see Appendix A, Section 3.

The symbol for beryllium is printed in italics to indicate that the isotope is unstable.

In this transmutation a confirmation of Einstein's theory of the interchangeability of mass and energy was obtained. If exact figures are taken, the combined mass of the two helium nuclei is less than those of the original proton and the lithium nucleus. The missing weight is precisely equivalent to the released energy predicted by Einstein's theory and observed in practice. This energy is some 18 million electron-volts, or 18 MeV. But only a few protons make collisions and the total energy put into the stream shot at the lithium targets is much greater.

In other words, the transaction does not pay, for it shows an overall working loss. It was clear to those who made such experiments in the early 1930's that if man was ever to be able to make use of the energy locked up in the nucleus, means would have to be found of making an overall working gain possible. Energy from the nucleus could never be of any practical value unless the amount obtained was considerably greater than the amount expended in obtaining it.

A ton of gold is worth a great deal of money. Yet one might easily own several tons of gold which were quite valueless; there must, in fact be many people who do so. Suppose that you possess a piece of land, the soil of which contains (as many soils do) minute traces of gold. Then your land may have under its surface many tons of gold. But to extract the metal would cost much more than you could obtain by selling it. Gold-bearing land is worth working only if the money from sales of gold amounts to a good deal more than the money spent in extracting it. Similarly, sources of energy are of no practical value, however great they may be, unless their energy can be extracted economically.

Nor, at first, did the radio-active elements seem to be

very promising sources of usable energy on a large scale. There is no doubt that they release vast amounts of energy in the course of their change into lead: the total energy released by one and a half pounds of radium in the process is, for example, a good deal greater than that produced by the burning of all the coal mined in Britain in a year. But the *half-life* of radium is some 1600 years; hence the total output of energy is built up by its continual slow release in comparatively small amounts.

To enable us to warm our bodies, cook our food and run our machines we need a rapid release of energy. The burning of a piece of wood or coal and the rusting of a bar of iron are similar processes from the chemical point of view. In each case the basic process is oxidisation. The carbon in the fuel combines with oxygen from the air to form carbonic oxide gas; iron combines with oxygen to form iron oxide, or rust. In both cases the combinations of atoms into molecules are accompanied by the release of energy. But you would remain a cold, hungry pedestrian if you tried to heat your home, cook your food and run your car by means of energy supplied by the rusting of iron.

Burning is a rapid process, with a release of energy concentrated into a small amount of time. Oxidisation of iron, on the other hand, is a slow business in which energy is set free in dribblets over a long period. The decay of radio-active elements into lead is much more akin to oxidisation than to burning, so far as the giving out of energy is concerned: a great deal of energy is released; but the rate of release is far too slow to meet the needs of man for any but a few special purposes. Doctors make use of radio-activity in their treatment of certain diseases; radio-activity is responsible for the luminous dials of some clocks and watches; alpha particles are used as ammunition in the physical laboratory. These and a few others

on a similar scale are about the only ways we know of making direct use of the energy released by the natural decay of radio-active elements.

The half-life of a radio-active element is fixed and immutable. It cannot be speeded up (or slowed down) by any known chemical process. Heat a piece of a radio-active substance to as high a temperature as can be obtained in the laboratory; cool it until its temperature makes as near an approach as we can contrive to absolute zero—the temperature of outer space; compress it under the greatest pressure that engineers and physicists can produce; place it in the highest vacuum that they can provide. . . . And the result? The radio-active matter shoots out electrons or alpha particles at exactly the same rate as it did before you tried to bully it into doing rather more. It defies every effort of chemist, physicist and engineer to induce it to speed up its natural rate of decay. . . .

Or, rather, it did until a remarkable new discovery, the importance of which was soon realised, was made by a former pupil of Rutherford's named Hahn. This discovery was that if neutrons were fired at uranium, a few of the uranium nuclei absorbed a neutron apiece and then split into two. Each of the two parts produced by this splitting, or fission, is the nucleus of a simpler element.

Every nuclear fission that took place released a comparatively enormous amount of energy in view of the tiny size of the atom concerned. Then why not obtain energy from uranium by shooting dense streams of neutrons at it? The answer is again that the position appeared to be that of the small-holder and the unwilling donkey: more energy had to be put into splitting uranium nuclei than could be obtained from the small number of fissions that resulted from copious, high-energy neutron bombardment.

In 1939 the key to this immense problem was found.

Any piece of uranium, that is of the metal as obtained from the ore from uranium mines, consists mainly of two isotopes, U_{92}^{238} and U_{92}^{235} . The first of these is about 140 times as common as the second and it is not "splittable," or, as the physicists say *fissile*, by the absorption of a neutron. It readily absorbs neutrons of certain energies (we shall see more of the process in a moment) and then undergoes a rather slow change with the release of no great amount of energy.

The reason why Hahn had found that only a few of his neutron projectiles caused uranium nuclei to split is that but a small proportion of them made head-on collisions with the scarce U_{92}^{235} nuclei in his uranium targets. This isotope of uranium "swallows" a neutron of any energy, becoming for a brief instant U_{92}^{236} . The effect of the entry of the neutron on the nucleus is spectacular. The nucleus is heated up and begins to "wobble" like a jelly; it expands and contracts in different directions; forms a narrow "waist" and splits into two separate nuclei. At the same time *it ejects two or even three neutrons*. That is the most important part of this extraordinary process. The nucleus receives one neutron and, as it splits, shoots out two or three.

In other words its output is greater than its intake, for each of the ejected two or three neutrons can go on to produce similar splittings of atoms of U_{92}^{235} . The process, once started, goes on rapidly until all available atoms have been affected. It is what is called a chain reaction, a reaction which keeps itself going once anything has occurred to give it a start.

A familiar example of a chemical chain reaction is the burning of the coal fire that warms our homes. It is started by applying a lighted match or a gas poker, to a layer of very inflammable paper. We call paper inflammable because its molecules need no very great input of energy

in the form of heat to make some of them begin such a violent combination with oxygen from the air that they burst into flame when the match is applied. The chemical combination of each paper molecule with oxygen liberates enough energy to make adjacent molecules start similar activity.

That is Part I of this particular chain reaction. The heat liberated by the burning paper is sufficient to start the molecules of the layer of sticks above it making similar violent chemical combinations and bursting into flame. The process goes on until all the wood is transformed into ash, smoke and gas; but meantime the heat energy set free by Part II of the process has (unless we have laid the fire unskilfully) caused Part III to begin. The molecules of coal need a good deal of heat energy to set their combination with oxygen atoms going. You could not make a lump of coal catch fire by means of a lighted match, or even of a considerable quantity of burning paper. The combustion of the sticks supplies the required heat energy and the coal begins to burn.

Again we have a chain of chemical reactions. The first molecules of coal to absorb enough energy to make them burn give out energy sufficient to cause neighbouring molecules to do the same. Soon a lump of coal here and a lump there are glowing or blazing. They emit heat energy sufficient to keep the process going, so long as fuel is supplied to the grate.

Coal is thus a profitable source of heat energy. Once the comparatively small amount of energy needed to set combustion going has been put into a mass of coal, it goes on burning until its chemical conversion is complete.

In Rutherford's experiments with the breaking up of nuclei no chain reaction could be obtained. It needed a comparatively large amount of energy ("firing" of high-speed alpha particles, protons or electrons) to produce any

splitting at all of nuclei. And when, perhaps, one in a million of his projectiles had produced splitting, or fission, of a nucleus this did not give rise to a chain of similar effects on neighbouring nuclei. To keep the reaction going you had to put in vastly more energy than was ever given out.

The heat energy obtainable from a coal fire would hardly be worth while if we could keep its emission going only by striking matches and applying them to it every few seconds.

CHAPTER XIII

Chain Reactions (2)

THOUGH WAR IS ITSELF a horrible thing, it may and often does produce certain good results. In peacetime nations are usually loth to spend much money on scientific research; work is thus handicapped by lack of funds. There is progress, but the rate at which it is made is steady rather than spectacular. When a nation's very existence is threatened by a modern war it turns at once to the scientist and asks him to invent or develop methods of helping it in the struggle. There is no shortage of money now: he can have all that he asks for and more. Progress is no longer made at a walking pace. It gallops.

Radio telegraphy and telephony, for example, made huge strides during the First World War. Each, when that war was over, offered inestimable benefits to Man. Every part of the civilised world is now linked with every other by means of radio telegraphy and radio telephony has brought happiness into countless millions of homes by means of its child, broadcasting. One of the noble products of the Second World War is radar, which is making travel by sea or air surer and more safe and has already been the means of averting many disasters that might have occurred had its aid not been there.

The other great advance in science made possible by that war was the harnessing of nuclear energy for the service of Man. The practical use then made of this energy was in the terrible form of the atomic bomb, in which every pound of uranium disintegrated had the effect of the detonation of several thousand tons of T.N.T. The initials stand for trinitrotoluene, one of the most violent

explosives of the rapid chemical chain-reaction type known till then for use in shells or bombs. The dropping on Japan of two of these bombs produced devastation so awful that the war was brought to an end long before it could have been won otherwise. Appalling as their effects were, these two bombs undoubtedly saved the loss of great numbers of British and American lives by bringing the war quickly to a close. Science may be proud of that achievement; but it is far from proud of the fact that it has given to humanity a means, if it is misused, of destroying civilisation and of bringing about something like a renewal of the Dark Ages.

Make no mistake about it. Nuclear energy, if misused by an aggressor nation in bringing about death, desolation and destruction by means of atomic bombs, could wreck the progress of civilisation and cause a return to primitive savagery. Actually, there is, as we shall see, no particular secret about the make-up of an atomic bomb. Given a sufficient supply of uranium and the means of separating the two most important isotopes of the metal, U_{92}^{235} and U_{92}^{238} , it is not an enormously difficult engineering problem to design a method of obtaining an explosion with effects far surpassing those of all known chemical explosives.

Fortunately, there are three great safeguards. First of all, uranium is a comparatively rare metal. Secondly, the most active isotope, U_{92}^{235} , represents only about seven-tenths per cent of the uranium present in any sample. Thirdly, the preparation of fissile material that will give the ultra-rapid chain reaction needed in the explosion of an atomic bomb is a long, elaborate and costly process.

Only two atomic bombs were dropped during the Second World War; but the work that made their production cost about £500,000,000. That sum would never have been found in peacetime for scientific research and development in the realm of nuclear energy. The fact

that the Americans and ourselves were fighting a war for survival against ruthless aggressors made the money available and enabled scientists to accomplish in less than five years of war work that might have needed fifty years of peace. If—and it is, one fears, a big if—mankind can become sensible enough to find ways of settling differences without fighting over them, this legacy from the Second World War will bring great blessings, for nuclear energy may serve a thousand useful purposes. If not . . .

The ample funds available to science in the recent war made it possible to explore two different methods of using uranium as a source of energy. The first was to devise a means of separating the scarce $^{235}_{92}$ isotope of uranium. This is clearly difficult business, for all isotopes of any element have the same sort of chemical behaviour. Two physical processes were devised, each very complicated, laborious and expensive. At the peak of its production effort in 1945 the gigantic plant erected in the United States to extract U^{235}_{92} had a maximum output of less than one pound of the pure 235 isotope per working day. This is not surprising when it is realised that to obtain the 235 isotope in reasonably pure form raw uranium must be put through between four and five thousand refining processes.

It hardly seems, then, that pure U^{235}_{92} is likely to be a profitable source of nuclear energy except possibly for very special purposes. It was used in the first atomic bomb. For the second, uranium was employed in a different way, which involved the manufacture of two previously unknown elements first on a small scale in the laboratory and then on a large scale in specially built plants of vast size.

When a mass of ordinary uranium, consisting mainly of the scarce 235 isotope and the far more plentiful 238 isotope is bombarded by neutrons a chain reaction does not occur. Very few of them reach U^{235}_{92} nuclei and cause

fissions to take place; and the secondary neutrons, ejected in the course of such fissions as do occur have a similar story.

An important point to grasp is that an atomic chain reaction can be sustained only if at each and every stage the output of *effective* neutrons is rather greater than the input. By an "effective" neutron is meant one which collides directly with a nucleus and produces a splitting resulting in the ejection of other neutrons, of which, on the average, rather more than one go on to make successful collisions. Unless these conditions are achieved, the reaction soon fizzles out, instead of developing into a chain.

Think again for a moment of the chemical chain reactions which make it possible to light a coal fire with matches, paper and kindling wood. The paper sets the sticks alight because, once combustion has been started by the match, each of its molecules when it combines with oxygen gives out rather more energy than it receives. The total output of heat energy from the paper grows until it becomes sufficient to set combustion going in the sticks. But we are assuming that the paper is dry. Suppose that it is damp, as most of us have found at one time or another, if an attempt to light the fire is not made until some days after it was originally laid. During that time the paper absorbs moisture from the air; and when we apply the match we find to our annoyance that the hoped for chain reaction does not occur. The paper flames for a moment, then smoulders and finally ceases to burn without having ignited the wood.

Apart from something rather more than annoying, what has happened? Part of the heat energy put into the paper has had to be expended in getting rid of molecules of water. This expenditure has been so large that it has mopped up a considerable proportion of the energy released by the combination of each paper molecule with oxygen. Instead of passing on rather more energy than

caused it to occur, each combination has undergone such wastage that the amount of heat energy given out by it is a little smaller than that which caused it to take place. Whether or not we are chemists, physicists or just ordinary people, the result is the same: the fire will not "catch." We have nothing but the melancholy necessity of re-laying it with dry paper (and, quite likely, dry sticks as well), if we want to start a successful chain reaction—though it is more than likely that we had never previously thought of applying that term to the lighting of a fire!

The U_{92}^{238} nucleus, of which the greater part of any sample of untreated uranium is composed, is not fissile unless a very fast, or high energy neutron collides with it. It absorbs the slower neutrons and has a special appetite (or resonance, as the physicists call it) for those with energies of about 40 MeV. By the absorption of a neutron U_{92}^{238} becomes U_{92}^{239} , for the mass is increased by one unit, though the units of positive charge remain the same: it is another isotope of uranium.

U_{92}^{239} is very unstable, for its half-life is only 23 minutes. An electron is then shot out, which has the effect of increasing the units of positive charge by one and of producing a nucleus of the previously unknown element neptunium Np_{93}^{239} . Neptunium is, again, very unstable. After $2\frac{1}{3}$ days a further electron is emitted and we then have a nucleus with a mass number of 239 and 94 positive charges.

This is another new element, plutonium, Pu_{94}^{239} . Whether plutonium has ever existed in nature is a moot point: but to-day, certainly, both plutonium and neptunium are purely laboratory products. Physicists have also produced artificially elements with atomic numbers 95 and 96 and there seems to be no special reason why it should not be possible to extend the range even further.

Plutonium is of high importance for three reasons. First of all, it is quite reasonably stable, having a half-life of

some 25,000 years; secondly, it is fissile under neutron bombardment and can therefore be used to release nuclear energy; thirdly, since it is a different element, and therefore has different chemical reactions, it can be separated from uranium by chemical methods.

The discovery of plutonium led to the working out of a new and more economical method of treating "raw" uranium. Carbon has the property of slowing down neutrons; in fact by using sheets of carbon of just the right thickness, fast high-energy neutrons entering at one side can be made to leave the other side at such speeds that they have an equal chance of being captured by the ^{235}U and the ^{238}U nuclei. In the pile used for the manufacture of plutonium, rods instead of sheets of carbon are used; and these are known as "moderators," because they serve to control the speed and energy of neutrons.

Suppose that bombarding neutrons of high energy (high speed) are fired into a mass of ordinary uranium provided with exactly the right number of carbon rods of exactly the right size. A general slowing down takes place. Some of the neutrons reach $^{235}_{92}\text{U}$ nuclei and cause fissions from which come further neutrons. These also undergo the slowing down process. Some of the slowed down neutrons are absorbed by nuclei of the ^{238}U isotope and cause it to change via neptunium into plutonium. The supply of neutrons able to bring about this change is increased by those ejected from fissions of the ^{235}U isotope. The pile, in fact, is nicely balanced, like a fire of good fuel in a well-designed grate. The $^{238}_{92}\text{U}$ is converted steadily into plutonium just as the coal is converted steadily into ash, smoke and gas. But some means of controlling the rate at which a fire burns is needed; it is provided by means of a damper or of air inlets below the grate which can be made wider or narrower at will. In this way the fire can be regulated to a nicety. Similar means of controlling the action of the

pile are also needed. The danger there is that its action might become too fierce. Heat is generated during the manufacture of plutonium and the rate at which this takes place must never exceed the rate at which the heat can be dissipated harmlessly. Regulating devices must also ensure that the stream of neutrons is always sufficient to keep the process of turning uranium into plutonium going.

The "damper" in the atomic pile consists of strips of cadmium. This metal has the property of readily absorbing neutrons without untoward effects. The cadmium strips are so arranged that they can be pushed in or pulled out as may be required. Should the pile show signs of operating too fiercely, an inward movement of the cadmium strips damps it down. If, on the other hand, the action is over sluggish, a slight withdrawal of the strips gives the necessary increase in activity. Actually, the movements of the cadmium strips needed to maintain the activity of the pile at neither more nor less than the required level are made entirely by automatic methods.

Most readers will be familiar with the action, if not with the working principles, of the thermostat. This is a simple, but enormously useful, device which makes use of the fact that metals in general expand when heated and contract when cooled. By employing suitable metals for their working parts thermostats can be designed to come into action at any desired point in a wide range of temperatures to operate electric switches, gas taps and other controls. Everyday domestic applications of the thermostat are seen in the automatic temperature regulation of the oven of the gas or electric cooker, the electric iron, the refrigerator and the immersion type of electric water heater.

In the pile used for the production of plutonium from uranium thermostats control gear which automatically moves the cadmium strips inwards or outwards and thus maintains the action at a constant level.

Plutonium is a particularly valuable source of nuclear energy for several reasons. It enables the whole of any mass of uranium to be used, instead of only the scarce ^{235}U isotope. It is comparatively stable, in view of its 25,000 year half-life, and can therefore be stored. In the course of its manufacture a huge amount of heat energy is liberated, and heat is the form of energy most readily employed to provide the power that Man needs so strongly to help him to produce and maintain a high standard of living. Last (and let us hope, least) plutonium is as fissile as ^{235}U , if subjected to neutron bombardment. It is therefore eminently suitable for use in atomic bombs.

We shall see in a later chapter how a form of atomic pile may be devised in which plutonium is subjected to fission and used up at the same rate as it is produced. The heat energy generated in the process is collected and may be used for industrial or other peaceful purposes. For the moment, however, we are discussing the kind of pile of which the primary output is fissile material in the form of plutonium. Here, the enormous amount of heat generated is merely something unwanted which, like the exhaust gases of the motor-car engine, must be got rid of in some convenient way.

The extraction of the desired plutonium from the pile is done in a simple, but very ingenious way. The raw uranium is inserted into holes in the carbon moderators. At suitable intervals some of the rods are withdrawn and the combination of uranium and plutonium now filling the holes in them is removed for chemical treatment. By this treatment the plutonium is separated from the uranium. The plutonium goes to swell the growing stock and the residue of unused uranium is replaced in the carbon to undergo further neutron bombardment. In this way all of the ^{238}U put into the pile is eventually converted into plutonium.

The Atomic Bomb

THE ATOMIC BOMB is the practical application of nuclear energy of which the ordinary man and woman has heard most. It had to come because the money and the man-power lavished on nuclear research during the Second World War had as their objective the saving of civilisation by the destruction in the most expeditious way of what were then the outstanding forces of evil. Probably no one regrets more than the true man of science that the atomic bomb should have been the first and hitherto the most striking practical demonstration of the possibilities of the harnessing of nuclear energy. At the same time, it must be remembered that this bomb brought the war to an end at least a year before it could have been concluded otherwise; it also spurred on the inquiry by the detectives of science into the nature of matter and showed beyond all doubt that nuclear energy could be utilised for the service of mankind, if Man has learned sense enough to devote to peaceful and beneficial purposes this new source of energy, in the development of which such rapid progress was made as one of the results of war.

There are no particular secrets now about the general principles of the atomic bomb. Any nation, in fact, could probably make it which—

- (a) had available sufficient supplies of uranium ore;
- (b) had developed the facilities for mining and refining this ore;
- (c) possessed the enormous plants necessary for separating the 235 isotope of uranium, or for producing plutonium in considerable quantities;

(*d*) had sufficient resources in money and in skilled man-power to undertake the necessary research, experimental and development work;

(*e*) contained large tracts of land, either uninhabited or readily cleared of inhabitants, in which trials could be carried out.

To produce an atomic bomb two things are necessary. In the first place, it must be possible to assemble in a container of reasonable size a quantity of fissile material in which a rapid chain reaction can be produced when required. In the second, it is essential to make absolutely sure that the chain reaction does not take place until it is wanted. In other words, it must be possible to store the bombs, for long periods if need be, or to convey them from place to place, with complete assurance that they will not "go off" until the right moment arrives and that they will not fail to do so when it does.

This double problem is solved in much the same way for both U_{92}^{235} and plutonium. Both are very dense forms of matter; but, as we have seen, the atoms of which any kind of matter is made up consist mainly of empty space. There is the compact central nucleus, containing nearly all the mass, or weight, of the atom, and round this the electrons revolve at comparatively enormous distances. Between the nucleus and the distant orbiting electrons there is just nothingness. There are intense electric fields, it is true; but these mean nothing to the neutron, which carries no electric charge and is therefore totally unaffected by them.

The result is that a neutron, discharged into even so dense a form of matter as uranium or plutonium, may travel a considerable distance before it makes a collision. The average distance that it does travel before being absorbed by a nucleus has been worked out in the physical

laboratory with the aid of the cloud chamber and other delicate apparatus. This distance is known as its mean free path.

For both ^{235}U uranium and plutonium the length of the mean free path of a neutron is a little over twelve centimetres, or roughly five inches. That is to say, unless a neutron travels through at least that thickness of either metal, there is an even chance that it will not collide with a nucleus, but will escape from the metal without having produced any effects. Such a neutron, from the nuclear energy point of view, is *ineffective*, since it does nothing.

We have seen that to keep a nuclear chain reaction going there must always be an increasing number of effective neutrons—of those which do come into collision with nuclei. Clearly, this condition cannot be fulfilled unless the size of the mass of fissile material is big enough to make it impossible for the majority of neutrons to avoid travelling inside it a distance rather greater than the length of the mean free path.

Make the mass of fissile material a sphere with a radius of little more than five inches and we have all that is required for a chain reaction. There is no need to start the process by any artificial neutron bombardment. The arrival from outside of a single neutron will “touch off” such a sphere of $^{235}_{92}\text{U}$ or plutonium—and there are always plenty of “stray” neutrons available, from cosmic rays and other sources, to set things going.

A sphere of either metal of this or larger size would, then, instantly blow both itself and everything else in its neighbourhood to pieces through the release of a huge amount of energy in a minute fraction of a second.

But if the mass of fissile material is smaller than this critical size, no chain reaction takes place. So many neutrons are ineffective, since they complete their mean free paths by an escape from the material without causing

collisions, that there are no violent results. Except for its radio-activity and for its slow breakdown during its long half-life, the metal remains perfectly docile. Any chain reaction that started would quickly fizzle out since too many neutrons would escape for it to be kept going.

Now suppose that two half-spheres of U_{92}^{235} or plutonium are made, each, say with a radius of five inches or somewhat more, and that they are kept (Fig. XIV.1) a

Hemispheres of uranium or plutonium

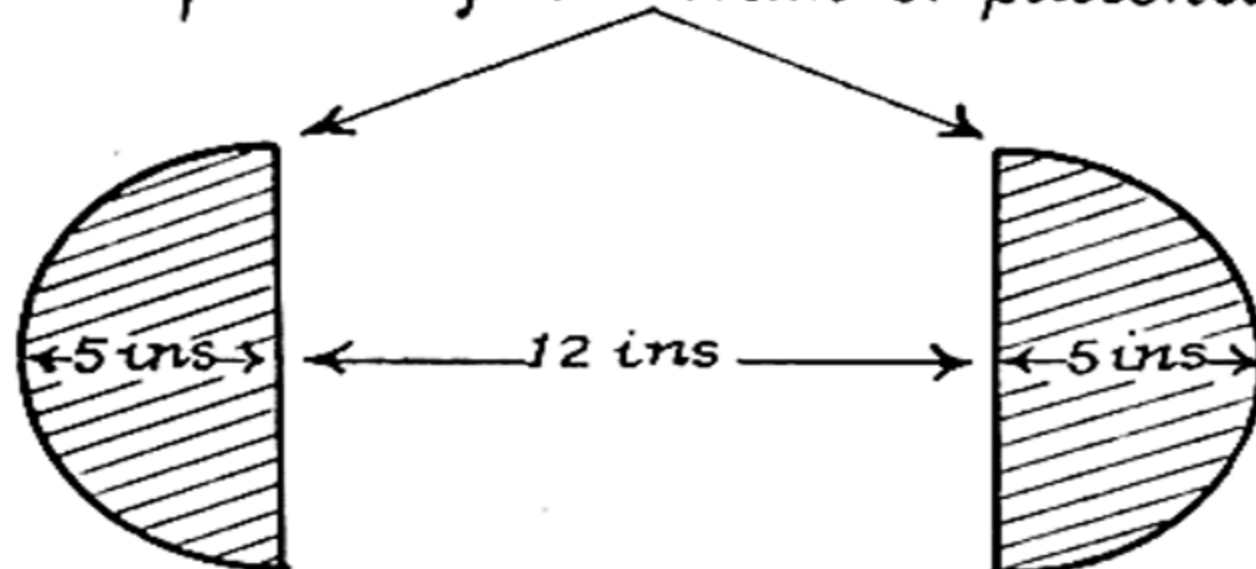


FIG. XIV.1. If two hemispheres of uranium 235 or of plutonium with a radius of 5 inches are kept separated from one another as shown, there is no explosion. No chain reaction can occur since too many neutrons will escape without causing fissions to occur.

foot or so from one another. The arrangement is perfectly stable in that nothing happens beyond normal radio-activity. Next, devise a means of clapping these two pieces

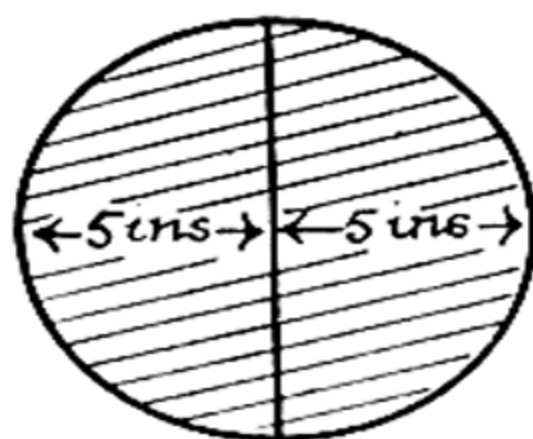


FIG. XIV.2. Bring the two hemispheres together and they form a sphere with a diameter of 10 inches. The majority of travelling neutrons now cause fission of nuclei. A chain reaction is instantly started and the radio liberation of energy is such that the most violent kind of explosion takes place.

of metal rapidly together (Fig. XIV.2) so that they make a sphere. The mass of metal is now such that the average free path of a flying neutron is inside it. At some point in

that path the neutron makes a collision. The number of effective neutrons grows, for comparatively few escape. The chain reaction is sustained until all the uranium is used up. The result is the almost instantaneous release of colossal amounts of energy in the form of blinding light, heat comparable to that on the sun's interior and gamma radiation of the most penetrating and destructive kind.

Actually, all of the uranium could not be used up by the method suggested. In the course of the explosion a moment would come at which the mass of metal was no longer big enough to sustain the chain reaction, which would fizzle out. That is probably why early bombs were classed as "inefficient." It is claimed that new methods have rendered the latest U.S. atomic bombs many times more efficient than wartime types.

No details of the atomic bomb have been published for

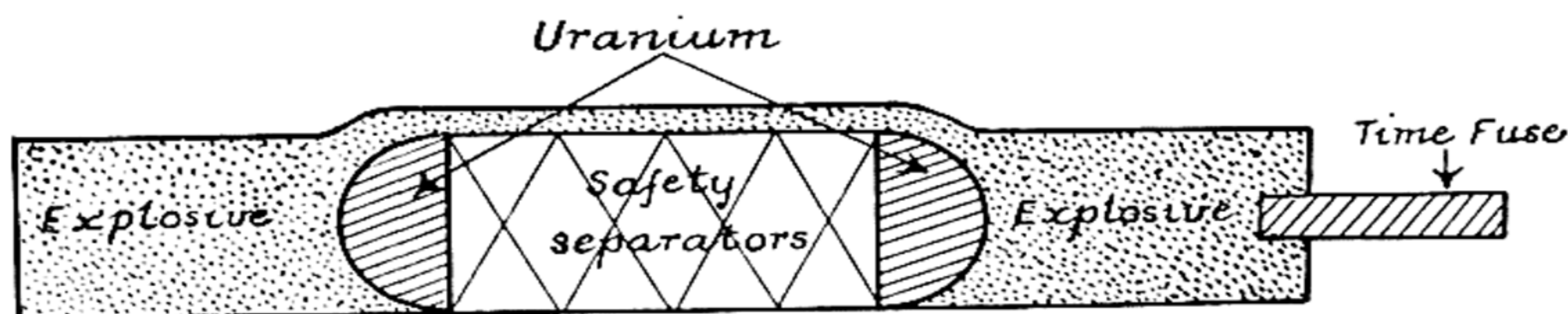


FIG. XIV.3. The general lines upon which an atomic bomb might be constructed. So long as the two hemispheres of fissile material are kept apart by the separators, the bomb is perfectly safe. But when the time fuse ignites the explosive charges and drives the hemispheres into contact with one another the most violent of chain reactions starts instantly, with devastating effects.

obvious reasons; but we may hazard two guesses about it. The first is that the weight of the fissile material which it contains must probably be not less than about 350 lb., in view of the weight of the smallest sphere of U_{92}^{235} or plutonium necessary for the chain reaction. The second is that its construction may be on the general lines indicated in Fig. XIV.3. The time-fuse detonates charges of some powerful explosive, such as T.N.T., which rapidly

brings together the separated halves of the sphere. The chain reaction instantly gets under way and in a tiny fraction of a second the most violent explosion yet conceived by Man takes place.

One point is worth noting. There are occasional reports of experiments in this country or that with "small atomic bombs." There can be no such thing as a small atomic bomb, for unless the mass of fissile material is of sufficient size to produce a predominance of effective neutrons no chain reaction, and no explosion, can take place. Nor, so far as one can see, is it possible on these lines for uranium bombs to be very large, since the two pieces of fissile materials that any contains must be so small that neither provides an average path for neutrons some five inches long. A bomb containing greater masses of fissile material would blow itself to pieces the instant it was assembled. It might, however, be possible to design larger bombs by dividing the fissile material into quarter-spheres instead of hemispheres.

Another point of some interest is that there is no very true ring about stories that atomic energy is being used for large-scale blasting for entirely peaceful purposes. One claim was that such blasting was directed to altering the courses of rivers: they would be made to flow through what had been arid deserts, thus rendering great new tracts of land habitable and productive. Any such operations would, in fact, probably make all forms of life, from Man to microbe, impossible in large areas for a long time to come. An atomic explosion produces radio-active isotopes of all kinds of matter, which may have lethal effects. A river diverted in this way might well consist of radio-active water and so be a destroyer rather than a life-giver.

Though the atomic bomb is the first means that Man has devised of producing explosions of such magnitude, it is believed that Nature occasionally brings about nuclear

chain reactions on a far grander and much more spectacular scale. From time to time some star which had been until then a small, dim object, visible only with the aid of a powerful telescope, suddenly starts to grow brighter and brighter. In a day or two it may become one of the most conspicuous objects in the night sky. Then its brightness fades as rapidly as it once increased. It is believed that such a "new star," or nova, as it is called, may be the result of a vast nuclear chain reaction, in the course of which a body as large as our own sun has a great part of its mass converted rapidly into radiation.

Energy is released when a uranium bomb explodes because the combined weights of the fragments into which each uranium nucleus is split are a little less than the weight of the original nucleus and the absorbed neutron. The "missing" matter has been converted into energy.

In the uranium bomb, devastating as it is, the proportion of the original matter so converted cannot exceed 0.08 per cent. A much greater menace to the existence of human civilisation is the hydrogen bomb, of which something is said in Appendix C (page 190). In this the proportion of matter convertible into energy is three times as great.

Controlled Energy from the Atom (1)

A RELEASE OF ENERGY such as occurs when an atomic bomb explodes is far too rapid and too violent to be usable for any kind of industrial purpose. Once that chain reaction has been set going it is completely out of control; but for peaceful purposes we need something which is readily controllable. One of the great problems now confronting science is to find a practical means of applying the energy which can be obtained from the splitting of uranium, plutonium and possibly thorium nuclei to turn the wheels of the electric generating stations, the factories and the many other fuel-consuming centres which play so important a part in the civilised life of to-day.

The plain and simple fact is that Man is using up the world's resources of ordinary fuels at an alarming rate. His present main sources of energy are coal, oil and wood, all of which are forms of "bottled sunshine." Coal, for example, is the semi-fossilised remains of the great trees, tree-ferns and other vegetation which once grew in profusion in certain areas of the world. Whilst they were growing these plants stored up chemical energy, obtained from the light and heat of the sun. When we burn coal we cause a chemical process to take place which releases the energy from the sun, stored up millions of years ago.

The result is, in many ways, entirely satisfactory. The heat energy released when coal burns gives us cheerful fires in our homes, drives the locomotives that pull our railway trains, provides gas for domestic lighting and cooking, furnishes our factories with the power that they

need, enables electricity to be generated at an economic cost and does a thousand and one other jobs which we now regard as essential, if our standard of living is not to suffer seriously. Oil and, to a rather lesser extent, wood are also vitally important providers of energy.

Water-power is largely used in some countries, such as Switzerland, Northern Italy, France, Sweden, Norway, Canada and parts of the United States, where lakes and large rivers suitable for the purpose are available. This source of energy has the important disadvantage that it is not entirely reliable. Prolonged drought is liable to have serious effects, as it did in Switzerland, France and Italy in 1948-9. The tides of the sea are a possible source of vast amounts of energy; but, so far, no economic methods of utilising them have been found: energy from the tides seems likely to cost more than it would be worth. It would be a magnificent achievement if we could harness the tides, for we should then be able to make the moon do most of the world's work, since the tides are due mainly to the piling up of the waters of the seas under the attraction of the moon.

There would be no fly in the ointment and nothing for the world's population to worry its two thousand million heads about if . . . Well, there are several "ifs" and we had, perhaps, better make a table to show what they are.*

Up to now the only really practical (as opposed to experimental) use that has been made of the energy released by nuclear fission is to cause explosions enormously more violent than any that can be brought about by chemical methods. There are actually three different kinds of process by means of which heat energy can be obtained from the chemical combinations of atoms. These are:

- (1) Combustion. (2) Explosion. (3) Detonation.

* See pp. 144-5.

The essential difference between them lies in the rapidity with which they take place. Combustion—the familiar burning of fuel—we have already discussed. The most important factor here in the release of heat energy is the combination at a comparatively slow rate of the carbon in the fuel with oxygen from the air to form the gas carbon dioxide, or CO_2 . No high pressures are set up in a stove or a fireplace, because the flue is easily able to dissipate the gas as fast as it is produced.

An explosion takes place in the chamber of a gun, a rifle or a cannon in a fraction (generally about one hundredth) of a second after the trigger is pressed or the firing mechanism brought into play. An explosion is simply very rapid combustion in a confined space. In a shotgun, to take one example, the smokeless powder propellant normally occupies the very small amount of space between the base of the cartridge-case and a rather thick wad, made of felt. When the trigger is pressed the striker hits the cap, causing it to ignite and to send an intensely hot jet of flame into the propellant. The chain reaction is continued by the propellant, which is rapidly converted into a large volume of gas and a small residue of solid matter. The pressure in the chamber quickly rises to rather more than 2 tons to the square inch, with the result that, as the wad fills the barrel and prevents gas from escaping past it, the charge is shot out with a velocity of about 1,000 feet a second. The process is similar in rifles and cannon, though wads are not necessary. The explosion here may result in pressures ten times as high as those in a shotgun and velocities from three to five times as great. In all cases heat energy is converted into energy of motion: the shot charge or projectile is driven forward and the weapon recoils owing to the backward motion imparted to it.

Detonation is a very rapid form of explosion, in which a

ENERGY APPLICABLE TO DOMESTIC AND INDUSTRIAL USES

<i>Source of Energy</i>	<i>Present Position</i>	<i>The Future</i>
I. COAL	Supplies being used up rapidly. Nature not replacing them. Mining becoming more and more difficult in many coal-fields. Still the most important source of energy.	Posterity will have to find a substitute for coal. This is specially important in view of the increase in the world's population and the rising standards of living.
II. OIL	Supplies, again, being used up at an increasingly rapid rate. New oilfields are being discovered and exploited; but the total amount stored up by Nature is definitely limited and cannot last long at the present enormous and growing rate of consumption.	Here, too, posterity must have a substitute.
III. WOOD	Not now one of the most important sources of energy. In any event the world's timber supplies are dwindling.	Not likely to be important as a source of energy.
IV. WATER-POWER	There will undoubtedly be big developments of this source of energy, for countless millions of gallons of water are now running to waste, so far as the provision of energy is concerned, in the majority of the world's rivers. The usefulness of this source is reduced by the fact that there are limits to the distance over which electricity generated by water-power can be transmitted economically.	Water-power cannot be expected completely to provide the substitutes needed for coal and oil, partly because of the limited distance at which its energy can be used economically; and partly because the supply is to some extent dependent on weather conditions.

ENERGY APPLICABLE TO DOMESTIC AND INDUSTRIAL USES

<i>Source of Energy</i>	<i>Present Position</i>	<i>The Future</i>
V. THE TIDES	<p>The apparatus needed to harness this source of energy would be very costly, so far as can be seen at present. One great difficulty is that the rise (and therefore the energy obtainable) is very small for a considerable period before high water and a considerable period after low water.</p> <p>Similarly, the fall is small for some time after high water and before low water.</p>	<p>There are great possibilities here, for the amount of energy potentially available is ample to supply all the needs of the densely populated world of future years.</p>
VI. WIND-POWER	<p>A good deal of use of this source of energy is made in some countries, notably Holland. The drawback here is that the winds are proverbially inconstant—and constancy is one of the chief essentials in any important power-source.</p>	<p>Like energy derived from the tides, that from the winds can be really useful only if some means is developed of storing economically the electrical energy into which it is converted. Only in this way, it appears, can a constant and level output of energy be maintained. No way of storing electricity economically is known at present.</p>
VII. NUCLEAR ENERGY	<p>Rapid progress is being made; but no method has yet been found of utilising any source of this energy but the break-up of the nuclei of a few rather rare radio - active elements. Nor, so far, can controlled heat energy at the temperatures required by industry be provided by nuclear fission at an economic cost.</p>	<p>? ? ?</p>

mass of high-explosive, such as T.N.T., is converted into gas and a small solid residue in a tiny fraction of the time. The effects are far more violent because they are so much more sudden.

From the point of view of the electronic or atomic scientist accustomed to dealing with millionths—or even fractions of millionths of a second—the one-hundredth of a second in which an explosion takes place is quite a long period of time! The pressure in any kind of gun rises comparatively gradually, giving time for it to be met by an expansion of the barrel and by a forward movement of the shot charge or projectile, by which the size of the chamber in which the explosion is occurring is steadily increased. Were the propellant in a gun, rifle or cannon to detonate, the weapon would be blown to pieces. The pressure would rise so rapidly that neither the barrel nor the charge would have time to accommodate themselves to it. This does not happen because in all the kinds of gunpowder used as propellants the chemical chain reaction which takes place is controlled: it cannot take place in much less or much more than one hundredth of a second.

The detonation of high-explosive in bomb, shell, mine, or torpedo is an example of a chemical chain reaction of the uncontrollable kind. In fact the more rapid and the less controlled the conversion of a high-explosive into gas, the more effective is it in producing devastating effects, both by flinging far and wide fragments of the metal envelope in which it was contained and by setting up in the atmosphere near the point at which detonation occurs those alternate high pressures and low pressures which produce blast.

The atomic bombs dropped on Japan, and those used later for minutely observed tests at Bikini, provided examples of super-detonations due to nuclear chain

reactions. Their effects were vastly greater than those due to any chemical detonation for several reasons, the chief of which is this. In a chemical detonation the very rapid reaction which takes place converts solid matter partly into an enormously greater volume of gas, partly into heat energy and partly into a small, but appreciable, residue of solid matter. The nuclear chain reaction of the atomic bomb is far quicker and it results in the almost inconceivably rapid conversion of uranium or plutonium into energy of several kinds. But, whatever the form of energy concerned, its output from such a super-detonation is too violent, too sudden and too uncontrolled to render it of any value for domestic or industrial purposes.

Explosions, as opposed to detonations, can be and are used as providers of energy useful in peace time. Familiar examples of this application are the internal combustion engines which drive our motor cars. Here, the explosion in the cylinders of a mixture of small amounts of petrol gas and air drives the pistons outwards and converts heat energy into energy of motion by causing them to make the crankshaft turn. But there is as yet no known way of obtaining a mild explosion from a small amount of fissile radio-active material. As we have seen, a chain reaction can occur only when a comparatively large amount of such material is used; and what then occurs is not an explosion, but something far surpassing in violence the most terrific detonation produced by chemical means.

So far, then, as can be seen, there does not appear to be any likelihood of our being able to use nuclear energy for working any kind of internal combustion engines. The only other important method that we know of turning heat energy into energy of motion is to use it to produce steam pressure. The steam makes wheels move by pushing against pistons or the blades of turbines. Once we have the wheels moving we can please ourselves whether we

use the power represented by this movement directly (as in the stationary engine, the locomotive or the motor car), or indirectly by applying it to generate electricity, which enables power to be conveyed over considerable distances by means of wires and cables.

Is there any means of controlling nuclear fission and of using it to supply the energy needed in factories and in homes? There seems to be a good chance of our being able to get a great deal of what we need—if not all of it—from a modification of the atomic pile described in Chapter XIII. The pile, it will be recalled, was designed originally for the manufacture of U_{92}^{235} and plutonium. In the kind of pile used to produce plutonium slugs of uranium are sealed into aluminium containers. These are inserted into holes in the carbon (graphite) “moderators,” or placed in the still better moderator “heavy water.” Ordinary water, it will be remembered, is a combination of two atoms of hydrogen H_1^1 , with one of oxygen O_8^{16} . The molecules of heavy water are made up of one atom of H_1^1 , one atom of the heavy isotope H_1^2 and one atom of oxygen.

When the pile is in operation an enormous amount of heat is generated in it owing to the radiation which results from each fission. About one million kilowatts is released for each kilogramme (roughly 2 lb.) of plutonium manufactured. In wartime piles, designed specially for the production of fissile material, this heat was simply something unwanted which had to be disposed of by getting rid of it in the quickest and most effective way. The great American piles at Hanford were erected on the banks of the Columbia River in order that immense supplies of water should be available for cooling purposes. All of the generated heat, in fact, ran to waste, its only effect being to raise the temperature of a short stretch of the mighty Columbia River by about one degree.

Controlled Energy from the Atom (2)

WHEN THE WAR WAS OVER and scientists turned gladly to exploring the possibilities of using nuclear energy for peaceful purposes it was at once seen that the most likely solution of the problem lay in utilising the heat which had till then been wasted.

From one point of view there appeared to be no great difficulty about adapting the pile itself to peaceful tasks. If you think for a moment about the operation of the pile used for manufacturing plutonium, described in Chapter XIII, you will see how this could be done. In that pile the commonest kind of uranium, the 238 isotope, is turned into plutonium by being bombarded by suitable neutrons. Some of these come from outside sources; others are released in the pile from the fissions of the rare isotope U_{92}^{235} . By correct adjustment of the graphite moderators and the cadmium control rods the supply of neutrons can be maintained at such a level that the bulk of the plutonium resulting from the capture of neutrons by U_{92}^{238} remains unaffected and can be separated from the uranium slugs by chemical methods.

But plutonium is itself a fissile element ejecting neutrons when its nuclei are split. If it is left in the pile, instead of being extracted, the neutron density inside the pile can be adjusted in such a way that the plutonium manufactured is destroyed by fission exactly as fast as it is produced. We then have a pile of which the main product is heat energy. The input is raw uranium, consisting of small amounts of the 235 isotope and very much larger amounts of the 238 isotope. During operation fission of

the 235 isotope is made to occur directly and fission of the 238 isotope indirectly by its conversion into plutonium. The result is that all of the uranium is used as fuel and that the output is millions of kilowatts of heat energy.

So far so good; but there is one very important snag: how are we going to collect the heat provided by the pile and to apply it to useful ends? The answer to that question may seem to have been given already. Why not extract heat from the pile by arranging water-jackets round the uranium slugs? Let some of the jackets be used for converting water into steam at high pressure; let this steam be super-heated in other jackets by the ample heat energy available; give engineers high-pressure super-heated steam and they will do the rest. There is no question that the break-up of a single pound of raw uranium can provide millions of kilowatts of the heat energy that we need if . . .

Those "ifs" . . . !

If we can find some way of harnessing it to do what we need, the energy is there. But heat energy is of little use for industrial or domestic purposes unless it enables us to obtain temperatures well above that (100°C.) at which water boils and steam is generated. Your garden, for instance, absorbs a large quantity of heat energy from the sun on a hot summer day and gives up a considerable amount in the course of the colder night; but though the amount of energy concerned is probably more than goes to heat your bath water or cook your food, you could not harness it for either purpose. The rate at which the energy is available is far too low. It is rather like being left £100 by the will of some eccentric relative. A hundred pounds, even in these days, is a nice, round sum, with which many desirable things could be bought—if you had it all at once. But in our imaginary case the will states that the legacy is to be paid at one penny a day and that no

payment is to be made until the previous day's instalment has been spent. A penny a day for sixty-six years means a negligible gain in your purchasing power. It is something very different from a lump sum of £100 paid down, even though it adds up to the same total in the end.

There are vast amounts of heat energy available from the fission of uranium in a pile; the temperature of such a pile may become dangerously high if the rate at which the consumption of uranium is not carefully controlled; but we know how to control it. Then why should we not arrange to collect heat from it at any desired temperature within reason?

To prevent unwanted chemical reactions uranium must be enclosed in sealed metal cans. Now, it is essential that these cans shall be made of some metal which does not itself capture any appreciable quantity of the flying neutrons; otherwise the working of the pile will soon come to a standstill. The chain reaction that we want can continue only if, on the average, each nuclear fission in the uranium results in the release of rather more than one effective neutron. By an effective neutron we mean in this case one which (*a*) causes a ^{235}U nucleus to split, or (*b*) makes a ^{238}U nucleus begin the transformation *via* neptunium into plutonium, or (*c*) produces fission in a plutonium nucleus. If a proportion of the neutrons ejected in the course of fissions in the uranium slug are just mopped up by the atoms of the metal of which the cans are made, fissions in the uranium soon produce too few effective neutrons to keep the chain reaction going.

A violent fire of intense heat is quickly extinguished (as those who shovelled sand on to incendiary bombs during the war may remember) if the chemical chain reaction which causes it can be slowed down to a point at which the chain is broken. Though few of them had then time to analyse causes and effects, A.R.P. personnel were then

engaged in damping out chemical chain reactions by starving conflagrations of the free oxygen necessary for their continuance! No kind of fire can go on burning unless there is a steady and ample supply of free oxygen atoms to combine chemically with the carbon atoms of the fuel. Next time you have difficulty in making a fire "catch" in one of your home grates you may find some consolation in that technical way of putting matters. In dry air, which is a mixture of gases, there is plenty of free oxygen. By applying sand, or a wet blanket, we prevent the access of air. The water of the fireman's hose is a compound containing little or no free oxygen. By any of these means the chemical chain reaction is arrested. Unsuitable metal in the cans of the pile would damp out the chain reaction by absorbing too many neutrons.

There are very few metals which are suitable as material for the cans in which the uranium slugs are sealed. Aluminium is one of them and it was used in the wartime piles designed for the production of U_{92}^{235} and of plutonium. This metal is cheap and plentiful and it is not a "neutron-snatcher"; in fact, in piles such as those mentioned in Chapter XV aluminium behaves admirably.

But—and it is a very big and important "but"—aluminium corrodes rapidly if the temperature of the cooling water, which collects and carries off the heat energy generated, much exceeds 100°C ., or boiling point. This did not matter in the least in wartime, when heat was a mere waste product of the pile. It does, however, matter greatly when we want the main output of a pile to be heat energy of the kind that is useful for industrial and domestic purposes. At the time of writing no complete solution of the problem of collecting heat energy at high temperatures from a pile is believed to have been found. Detective work is being pressed forward intensively and by the time that this book appears in print it is more than

likely that several high-energy piles will be in full operation. Either some alloy more suitable for the purpose than pure aluminium will have been found, or methods will have been worked out of using heat-collecting agents which do not cause corrosion at high temperatures.

CHAPTER XVII

What does the New "Fuel" offer?

ASSUMING ALWAYS THAT NO nation or combination of nations becomes so insane as to misuse it in order to force upon the rest of the world a new war, what has the harnessing of nuclear energy to offer to humanity? That is an assumption vitally important to you, to me and to every human being. Any new war could not fail to wreck civilization by bringing into play appalling misapplications of the advances that science has made in physics, chemistry and biology. Such a war would be unthinkable folly. Whoever emerged as the victors, no one could gain anything from it. The destruction would be on so frightful a scale that the clock would be put back by at least a thousand years and the only possible result must be a return by a large part of the now civilised world to semi-barbarism.

Properly used, nuclear fission may do much to make the world a better place by providing new sources of energy for a large number of beneficial purposes; but it must not be imagined either that complete solutions of all the problems involved in obtaining this energy at economic cost are just round the corner, or that the nucleus can replace all the other sources of energy that we now rely upon. For the time being it seems that the only practical method of obtaining and applying nuclear energy for some years to come will be in the use of huge, stationary generating stations.

The pile in which usable nuclear energy is produced must be very large and very heavy. The reason is that the splitting of a nucleus is accompanied by both the radiation

of gamma rays, far more penetrating than X-rays, and the emission of neutrons, which may have destructive effects on the atoms that they encounter as they fly. Neutrons and gamma rays alike produce dread results on living things. Hence a pile must be completely enclosed not only by a thick layer of carbon, which reflects back into it the bulk of the neutrons that would otherwise escape, but also by many feet of solid concrete.

It is conceivable that a pile such as we now know it might be built into a ship of the largest size; but it could not form part of a motor car, an aeroplane or the familiar railway locomotive. True, a large stationary pile may provide the means of generating enormous amounts of electrical power. One can readily imagine such a pile operating the generators which supply light, heat and power to every home, shop or factory of a great city. Again, it might serve such forms of public transport as electrified railways and trolley buses by providing cheap supplies of electricity. Then why not have electric motor cars and aeroplanes? The answer is that we do not know any means of storing electricity without the use of bulky and heavy apparatus. Electrically operated motor cars can be, and are made. But the size and weight of their storage batteries is limited both by the space available and by consideration of the load which can be carried economically. Hence, the electric car can make only a short run at moderate speed before it has to have its storage batteries recharged. Even if "refilling" points for the batteries of electrically driven cars were provided every few miles along all roads; even if the cost of recharging were very small indeed, the motorist's dream of being able to drive speedily and cheaply from one place to another would not be realised by any application of nuclear energy that we can foresee at the moment. Storage batteries are expensive to install

and their useful life is limited. Their weight is just an addition to the "useless load" of the vehicle, to say nothing of its effect on the wear of springs, bearings and tires.

If stored electrical power is not an economic proposition in the case of the motor car, other than the town runabout vehicle, it becomes something quite unworkable in the aeroplane. Here every inch of space and every pound of weight are of much greater importance. Nor, supposing that the necessary vast numbers of aerodromes were provided, could an aeroplane maintain a high average speed, if it had to land every few miles in order to recharge its batteries.

This is not to say that methods of storing electrical energy, or some other form of energy, by means of some quite different kind of apparatus, costing much less initially, having smaller weight and deteriorating less rapidly, will not be found. We do not now know how to do this—but less than a dozen years ago we knew of no means of obtaining energy from nuclear fission.

One of the biggest problems to-day is to find a satisfactory method of disposing of the by-products of nuclear fission in any kind of pile. The by-products of the generation of energy by chemical means may be annoying, but they can be dealt with without any great amount of trouble or expense. Many of those of the atomic pile are harmful; some are so noxious that even small quantities of them have deadly properties. It may be recalled that the after effects of the two atomic bombs used during the war were terrible. Many substances were made radioactive by the explosions and remained so for a long time, with fatal results to animal life of all kinds.

It used to be believed that only a few elements could show radio-activity: uranium, thorium, actinium, radium and polonium. It is now known that radio-active isotopes of the great majority of elements can be produced by

neutron bombardment and it seems probable that in time it will be found that there is no element which has not one or more radio-active isotopes.

The radio-active by-products of an atomic pile are similar to those of an atom bomb explosion. When a nucleus of the 235 isotope of uranium undergoes fission it splits into two fragments, ejecting two, or sometimes three, neutrons as it does so. The weight of the fragments plus that of the ejected neutrons is only 99.9 per cent. of that of the original nucleus plus that of the captured neutron which causes fission to take place: 0.08 per cent. of the original mass is converted into energy. The fragments are nuclei of other elements, the mass numbers of which together add up to 99.92 per cent. of the original mass (235 units) plus the captured neutron and minus the two or three ejected neutrons:

$$235 + 1 = 236; \quad 236 - 2 = 234; \quad \text{or} \quad 236 - 3 = 233$$

The fission products may be any pair of elements satisfying these conditions. As a rule, though, they are not widely unequal in mass; the most frequently produced pairs have one fragment about one and a half times as heavy as the other. But *all* of the isotopes resulting from nuclear fissions are radio-active: most of them eject an electron and a quantum of gamma radiation before reaching stability.

Some are quite easily dealt with, since their radio-active state is short-lived; if these are kept for a little time, they cease to be radio-active and can be disposed of into the air, into rivers or into the sea with perfect safety. Others, though, have radio-active half-lives running into hundreds or even thousands of years. It is these which provide one of the thorniest problems, if nuclear energy is ever to be used on a large scale.

This problem will undoubtedly be solved, though it is

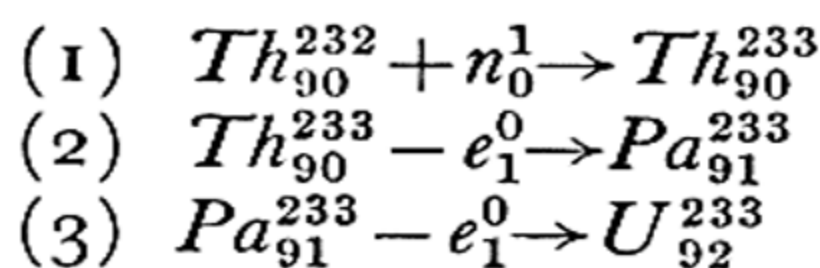
difficult to see where and how the solution is to be found. It is on a par—though on a far grander scale—with the problem which faced the first primitive man who wanted to keep a wood fire going in his small cave-dwelling. Until some early genius invented the smoke-hole, and a very much later genius the chimney, as a means of getting rid of the noxious by-products of combustion, those who went to sleep warmed by an indoor fire were apt never to wake again. What the atomic equivalents of smoke-hole and chimney will be we do not know. Possibly some method will be found of making fission products cease quickly to be radio-active. Or, again, it is possible that we shall discover ways of turning many fission by-products into useful nuclear fuel. Then the fuel of the pile of the future, the waste products of to-day, may consist of isotopes of various elements, which are harmless in themselves, or rapidly become so owing to their very short radio-active half-lives.

One thing is certain: the generation of energy by means of atomic piles cannot be developed on anything like a world-wide scale until the problem of disposing safely of radio-active by-products is solved. It will be realised how vast a problem this is when it is mentioned that everything which comes into any sort of contact with the enormous activity within the pile is liable to become radio-active. This applies, for instance, to water circulating round the containers of the uranium slugs and collecting heat from them. The wholesale discharge of large quantities of radio-active effluents into rivers, or even into the sea, might have dire results.

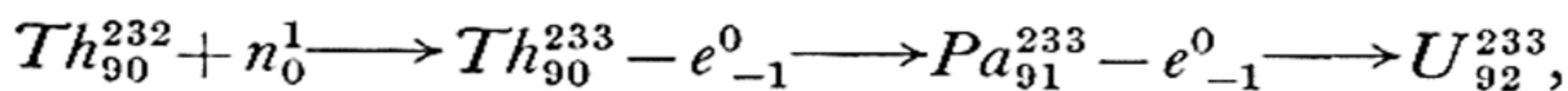
The next point to consider is that uranium, which has so far been the chief atomic fuel is neither very plentiful nor very widely distributed. Though a pound of uranium goes a very long way, the world's known supplies of the metal are far from unlimited. New sources are being

discovered, but there is not enough uranium, obtainable at economic cost, to provide even a fraction of the energy likely to be needed by human beings for domestic and industrial purposes. ✓

There can be little doubt that other sources of the fissile materials needed as fuel by an atomic pile will be found and exploited. Thorium, for example, which is much more plentiful than uranium has interesting possibilities. Under bombardment by slow neutrons the nucleus of Th_{90}^{232} captures a neutron and becomes a new isotope of thorium, Th_{90}^{233} . This isotope is very unstable; it soon ejects an electron, thus gaining one positive charge and going up one place in the scale of atomic numbers. It becomes, in fact, an isotope of protoactinium, Pa_{91}^{233} . Again an electron is shot out and once more the nucleus rises one place in the atomic number scale, becoming this time an isotope of uranium, U_{92}^{233} . We can set down the step of the transformation in shorthand form, again denoting the unstable isotopes by italics:



Or we may show it even more concisely as:



where the arrow stands for "becomes" or "turns into." If you have not forgotten your algebra, you will appreciate that minus minus one is equal to plus one. This shorthand notation thus shows how and why the loss of an electron makes the atomic number go up by one.

The 233 isotope of uranium produced in this way can be separated from the rest of the thorium by chemical methods. It appears to be as ready as U_{92}^{235} or Pa_{94}^{239} to

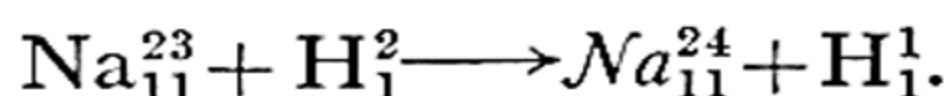
undergo fission when subjected to neutron bombardment. Methods of employing the relatively plentiful element thorium as a source of atomic fuel are likely to be developed; and it is not impossible that in the course of this development other sources of atomic fuel may be discovered.

Useful By-products

ALL OF THE BY-PRODUCTS of nuclear fission in the atomic pile are radio-active, as we have seen. Radio-activity can be dangerous to life and limb; but it has, fortunately, also its beneficent side. Were you to keep even a minute piece of radium in your pocket for a week or two, the results would certainly be unpleasant and might well be fatal, for the radiation from these substances has marked effects on the living cells of which the body is built up. Happily, this action is, to a considerable extent selective: the cells of certain malignant growths are much more sensitive to it and more readily destroyed by it than those of normal, healthy tissue. Hence the subjection to gamma radiation from radio-active substances of a part of the body in which some cells have become malignant may result in the destruction of these, whilst the normal cells remain unharmed. The use of radio-activity for such purposes must, of course, be very carefully regulated; for bombardment that is over-intense or is applied for too long a time damages the healthy as well as the unhealthy cells.

Medical science has found ways and means of determining the correct "dosage" of radiation for each particular case and the treatment has brought relief to a large number of sufferers. The number would have been even greater but for the fact that until recently the only known sources of the kind of radiation essential for the treatment of many cases were the very scarce elements radium and radon; the latter, sometimes still called "radium emanation," is produced during the break-down of radium.

Some of the radio-active by-products of an atomic pile are found to provide exactly what is needed for medical purposes. Atomic piles and other apparatus used in nuclear research stations are now supplying suitable radio-active isotopes of various elements in considerable quantities to hospitals, with the result that far wider use is being made of gamma radiation in the treatment of many kinds of maladies. A most useful radio-active isotope readily produced in the physical laboratory is radio-sodium. Sodium, symbol Na, is a very common metal. Ordinary salt is sodium chloride and we know that there is plenty of that both on land and in the waters of the sea. If sodium Na_{11}^{23} is bombarded with heavy hydrogen H_1^2 , the sodium nucleus captures the neutron of the heavy hydrogen, with the result that we now have the isotope Na_{11}^{24} and ordinary hydrogen H_1^1 . In shorthand:



Na_{11}^{24} is an unstable isotope, emitting an electron and gamma radiation. The loss of the electron raises the atomic number by one and it becomes magnesium Mg_{12}^{24} . The radiation emitted in the course of this latter change is several million times as intense as that from the same weight of radium. Hence minute quantities of radio-sodium are as effective as far larger quantities of radium. As the production of radio-sodium is comparatively cheap and as there is no special difficulty about manufacturing quantities as effective as many pounds of radium, its usefulness is easily realised. Few even of the largest hospitals once possessed more than a few milligrams of radium (a milligram is $\frac{1}{1000}$ gram, or, roughly, $\frac{1}{30000}$ ounce); now the needs of all hospitals are being met fully, not only by supplies of radio-sodium from atomic laboratories, but by a steady stream of equally useful radio-active isotopes of other elements from atomic piles.

An enormous new field for investigation by scientist detectives of medicine, biology and agriculture has been opened up now that certain mildly radio-active isotopes of many elements, with very short half-life periods, have become readily available as by-products of the atomic pile. Doctors want to know just which organs of the body are affected by certain drugs. Again, if it is important that a particular organ should not be stimulated (or depressed), they want to find out whether drugs of various kinds will or will not reach it, should they be administered as medicine. Biologists have all sorts of similar queries about the absorption or non-absorption of substances by the cells of the living creature. Specialists in agriculture are eager to find out exactly how fertilisers and weed-killers act upon the cells of plants.

Owing to the radiation which comes from them the presence of radio-active isotopes is readily detected by means of delicate, but quite simple, instruments. The departments of science interested in the health of human beings, of animals and of plants, in the production of foodstuffs, in the maintenance of fertility in the soil and in the control of animal and vegetable pests are obtaining valuable help from an entirely new technique, founded upon the use of tracer elements.

Tracer elements are those which contain a small proportion of artificially produced radio-active isotopes of very short half-life. Natural radio-active substances, such as radium or uranium could not be used safely. Owing to their long half-lives and to their intense radio-activity, they would have devastating effects on living tissues. From the large variety of radio-active isotopes which are now available, either as by-products of the atomic pile, or as products of the nuclear physics laboratory, it is comparatively easy to select a whole range of those that are perfectly harmless, owing to the rapidity with which their

radio-activity fades out, and yet emit for a brief period radiation intense enough to enable them to be located with precision.

Be sure, by the way, that you don't confuse *tracer* elements with *trace* elements. Science is, unfortunately, better at doing things than at talking or writing about its activities. Hence, it not infrequently uses terms which make things rather difficult for the layman. One example of this is to be found in the employment of the word "isobar" to denote an isotope which has the same mass number as another which belongs to an entirely different element. For example, there are atoms of platinum, gold and mercury which all have the mass number 199. These are for platinum Pt_{78}^{199} , for gold Au_{79}^{199} and for mercury Hg_{80}^{199} . Isobar would be an excellent word for the purpose (it comes from two Greek words meaning "equal" and "heavy") if it were not for the fact that it is already in use by another branch of science, with an entirely different connotation: the isobars with which large numbers of people are familiar are the lines on a weather map which show areas where the same readings of the barometer have been recorded.

A *tracer* element is one which is deliberately made to contain a proportion of radio-active isotopes in order that its absorption by organs or cells of the body may be studied and measured. A *trace* element is something very different. Zinc, copper and boron provide examples. Any of these, if administered in measurable quantities, is poisonous to most plants; yet amounts of one or other of them, so minute that they defy most attempts at measurement and are recorded merely as traces, are essential to the well-being of many kinds of plants. Animals, also, cannot flourish without almost incredibly tiny amounts of certain elements, of which anything more than minute traces would prove harmful, if not actually fatal.

We have discovered just a few of the useful by-products of an atomic pile. The number is likely to be considerably extended as the detective inquiry into the nature of matter, now so intensely pursued, brings more and more new facts to light.

CHAPTER XIX

Looking Ahead

MANY PEOPLE ARE DISPOSED to indulge in two rather vain imaginings. The first of these is that all the immense problems bound up with the harnessing of nuclear energy are likely to be solved within a year or two. The second is even more widely prevalent. It is that, once nuclear energy is available to make the wheels of industry go round, a modern Utopia will straightway come into being, for Man will be freed from a great deal of the toil that is now his lot. Each of these ideas is about as wrong as it could be and we had better see why.

The main reason why no perfect solution of the problem of using nuclear energy is likely to be found at once is that there is not sufficient uranium to supply our needs. It has been calculated that if uranium were used to furnish all the energy that the world needs to-day the known deposits of high-grade ore would be completely exhausted in less than two years. Up to now all the "fuel" for atomic pile has been obtained from high-grade ores. There are considerable deposits of lower-grade ores, but it is a much more expensive business to extract from them uranium which is sufficiently pure to keep the necessary chain reactions going. Cheaper ways of getting suitable uranium from low-grade ores may well be worked out; but, even so, the problem would not be solved for the supplies of ore are limited.

The only fissile material which occurs in nature is the $^{235}_{92}\text{U}$ isotope of uranium—and of every pound of pure uranium this isotope constitutes little more than one-tenth of an ounce. In the first atomic bomb the "explosive" consisted entirely of U_{92}^{235} , but this was found to be

too costly and altogether too prodigal of available material. For the only other atomic bomb used during the 1939-45 War (and, it is believed for others, whether existing or contemplated) a more economical method was adopted, as we have seen. In a special type of pile the scarce 235 isotope of uranium was caused to produce comparatively large amounts of an artificially made fissile material by ensuring the conversion of the much more common non-fissile 238 isotope of uranium into a fissile isotope of a new element, plutonium. Nuclear physicists call this process "breeding" because it enables relatively large quantities of fissile matter to be produced artificially by suitably "mating" the scarce 235 isotope of uranium. Fissile material can also be bred from thorium by mating the not over scarce isotope Th_{90}^{233} with the 235 isotope of uranium.

The fissile material bred in either of these ways can be stored and later employed to breed further supplies of isotopes suitable for fuel. We certainly cannot afford to use up our small natural supplies of fissile material as fuel in atomic piles. Still less can we afford to squander them in the making of bombs designed purely for destructive purposes.

There are, though, other enormously important possibilities. Nature may be aided artificially, as the first Neanderthal woman discovered who smeared her blubbery lips with red ochre; and as her female descendants ever since have endeavoured with varying success to demonstrate by the use of an unending variety of devices, intended to mitigate their shortcomings in colour, height, bulk, smell, shape and so on! Science, of course, is concerned with more serious and more probably successful aspects of the problem of prodding Nature to do a better job. By means of devices, such as the cyclotron, which are described briefly in the appendix to this book, it is

possible to produce streams of protons, deuterons (nuclei of heavy hydrogen) or alpha particles (nuclei of helium) far denser and of far greater energy than any provided by Nature. It is mainly owing to the action of these fast-flying particles of enormous energy, released by apparatus designed by the modern detectives of science, that the nuclei of nearly all known elements have been broken up or built up into radio-active isotopes.

It is rather more than possible that apparatus of this kind, if put into use on a large scale, may enable us to breed fissile material in unlimited amounts from elements far less rare than even low-grade uranium or thorium. At present the cost of constructing and operating big cyclotrons, synchrotrons and kindred apparatus is stupendous; but new and cheaper ways of producing the high-speed missiles needed for nuclear bombardment will no doubt be found.

There is, though, another possibility which seems to be yet more promising. So far, our detectives have discovered ways of obtaining energy by breaking up the nuclei of a few elements with high atomic numbers into others with smaller atomic numbers. The processes now in use depend, in a word, on the turning of the most complex nuclei known into simpler bodies. The nucleus of uranium 238 consists, for example, of a combination of 146 neutrons with 92 protons and this combination is broken up by fission into two (or sometimes three) simpler nuclei and two or three violently ejected individual neutrons. The nuclei so broken up belong to some of the rarest elements that our Earth contains. Even if the supply of them were inexhaustible (which is very far from being the fact), it would be unsound policy to regard them as the fuel of the future, for costly fuel, no matter how efficient, cannot provide the low-cost energy that human beings so badly need.

As has been mentioned in an earlier chapter, Nature works in exactly the opposite way in the great sources of energy that she provides in the sun and the high-temperature fired stars. What she does is to take the simplest and one of the most plentiful of elements and to cause energy to be released by making its nucleus capture other particles and become something more complex. Nature builds *up* from hydrogen, whose atomic number is one, by making its nucleus increase both its weight and its electric charge: her supplies of energy are based, so to speak, on the promotion of simple elements in the table of atomic numbers and weights. She obtains her results by causing common elements to be transformed into rarer ones. We, on the other hand, have so far not been able to find any better way than to supply destructive rather than constructive methods. Fission releases energy by breaking *down* complex nuclei by degrading instead of promoting elements in the atomic table, and by turning the rarest elements into common substances.

Could science find a way of imitating Nature in the use of common elements as providers of controlled nuclear energy, Man would be on the threshold of a wonderful new era of progress. But even if the world's power supplies could be obtained at negligible cost from the release of nuclear energy, Man would not be able to get along by doing hardly any work. It has been calculated that if unlimited supplies of power became available at minute cost we should all of us find that our working week had been shortened by not more than a single hour. Whatever discoveries and advances he may make, there seems little likelihood of Man's being able to escape from the decree, "By the sweat of thy brow shalt thou eat bread."

CHAPTER XX

Conclusion

TAKING STOCK OF THE position to-day, we cannot help realising that the greatest of all detective stories has not yet reached its *dénouement*, for we still have no final answer to the question that man has been asking through the ages: What is matter? Only a few years ago it seemed (as it has so often seemed in the past) that the complete solution of the problem was almost within sight. New kinds of particle, such as the neutron and the positron, had turned up to upset the earlier picture of the atom composed entirely of protons and electrons: Einstein had caused a considerable flutter by showing that mass and energy were different forms of one and the same thing; but all of these things had eventually been fitted into their places in the great jigsaw puzzle. There appeared to be very few gaps left in it and, so far as could be seen, the pieces needed to fill them were on the table. Then came the discovery of the meson. And not just of one kind of meson; but of heavy mesons, light mesons, positive mesons, negative mesons and neutral mesons. To make the mesons fit in it may be that we shall have to alter considerably the picture of the atom, which not long ago seemed so nearly complete. And who can say that when this has been done the discovery of new particles, or further discoveries about known particles, may not make yet another recasting of ideas about matter necessary? The neutrino has added further complications. The complete solution may come soon; it may be delayed for many years; it may even prove to be something too difficult for the mind of Man to grasp. But so long as

there is still something remaining to be known the detectives of science will continue to be hot on the trail.

As regards energy from the nucleus of the atom, we have found out a great deal. We know how to obtain the most violent explosions, followed by terrible after effects, from the fission of one of the rarest elements. We have also developed means of controlling the output of such energy so that it may be applied for useful purposes. We are, though, faced by three hard facts. The first is that the natural supply of elements which can be used as sources of nuclear energy is very limited. The second is that up to now no means has been found of generating controlled nuclear energy save the atomic pile of enormous size and weighing many tons. The third is that no entirely satisfactory way has yet been worked out of disposing safely of the by-products of a large-scale pile, many of which are capable of terrible effects on all forms of life.

There can be little doubt that all these difficulties will be surmounted in time. How soon answers to these pressing questions will be found or how long they may be delayed no one can say. Progress, though, has been amazingly rapid in recent years. A large generating station operated entirely by nuclear energy is now under construction in the United States. It is expected that the cost of electric power supplied by it will be less than 25 per cent. higher than that from a station of similar capacity operated by coal. Fissile material is still a more expensive form of fuel than coal; but remember that we are as yet only in the early stages of finding out the best ways of using it.

Only a few years ago the harnessing of nuclear energy was no more than a matter of speculation, for no one had then succeeded in producing fission of a nucleus of uranium. It is surely a proof of astonishing progress that in this short time the development of nuclear energy has

been carried so far that any kind of comparison with coal-operated plants as regards running costs is possible. If we have seen such advances in the few years just past, we may be sure that science has even greater marvels in store for the years that lie ahead.

APPENDIX A

Tools of the Trade

VERY FEW OF THE TOOLS used in the scientific detective laboratory for investigating the nature of matter have been even briefly described in the body of this book. The omission of such descriptions was deliberate; the appendix is not just an afterthought. I left out the descriptions because some people are not particularly interested in the ways in which things work and find it difficult or dull (or both!) to follow explanations of laboratory instruments and how they do their jobs. I did not want to frighten off such readers, or to give them the impression that fairly satisfactory general ideas of the modern view of the nature of matter or of the harnessing of nuclear energy cannot be formed without knowing something of the apparatus used for research purposes.

Simplified explanations of some of the most important devices follow. They will, I believe, be helpful to those who wish to read more advanced books on the subject of atomic energy; but they may be left unread by those who are content to take the results for granted and are not interested in the ways in which they are obtained.

I. ASTON'S MASS SPECTROGRAPH

The discovery that there could be different kinds of the same element was made by J. J. Thomson. The fact that a quantity of any element consisted of an assembly of atoms of the same atomic number, but not necessarily of the same mass, was discovered (Chap. VII) by F. W. Aston in 1922. For this work he devised an instrument which he

named the mass spectrograph. It has since been improved in many ways; but the mass spectrographs in use to-day in nuclear physics laboratories use the same basic principles as Aston's 1922 instrument.

Fig. App.1 illustrates diagrammatically and in very

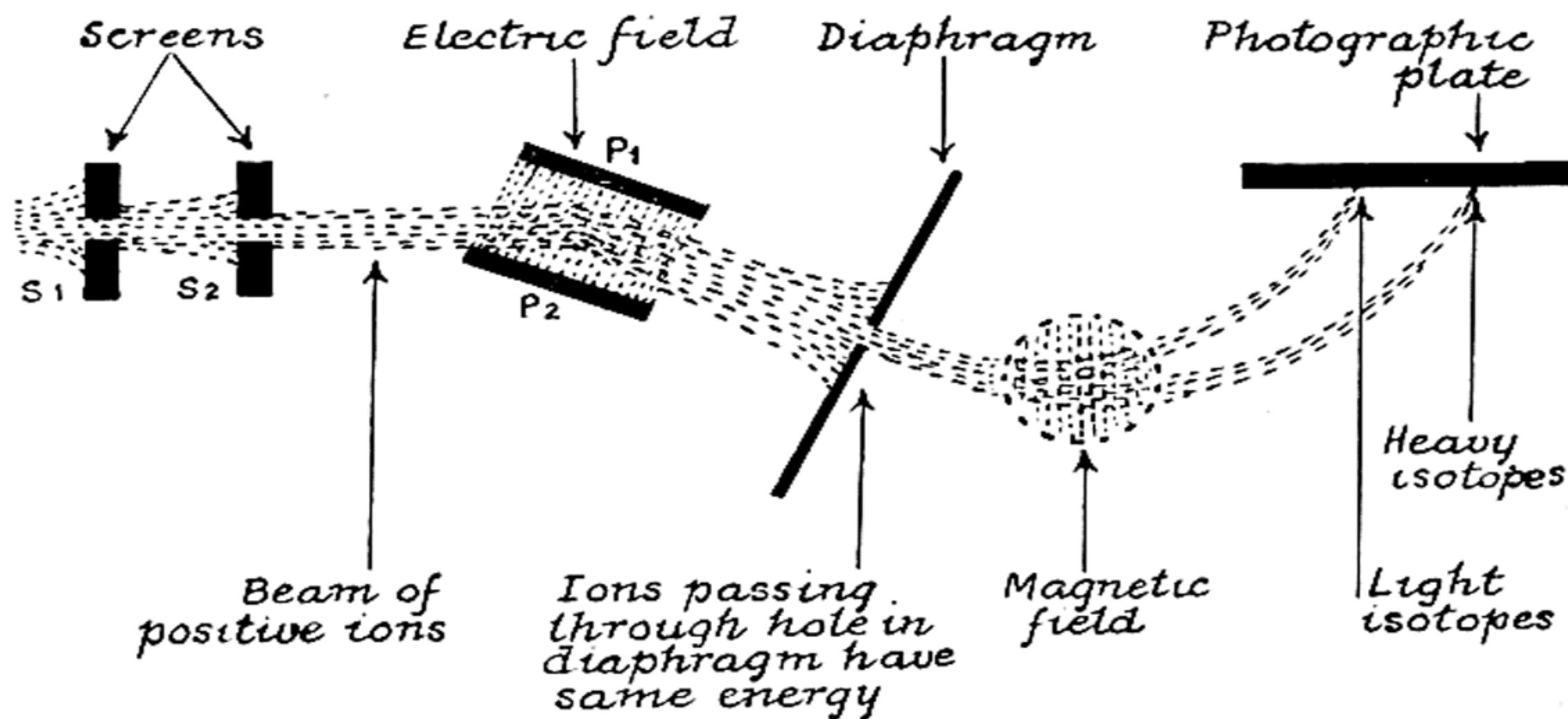


FIG. APP.1. The principle of the Aston Mass Spectrograph. Ions arrive from a source to the left of the drawing which is not shown. All of the parts are housed in an evacuated container, which is also omitted in order to simplify the diagram.

much simplified form the way in which the device sorts out the different isotopes and makes them record their presence. For the purposes of this explanation an element is taken which has only two isotopes, a light and a heavy. From a source (not illustrated) to the left of the diagram a stream of atoms of the element under examination is directed on to the first screen. The atoms are in the form of positive ions. Some of them pass through the slit S_1 and travel towards the second screen in which is another slit S_2 . The effect of the screens and the slits is to produce a narrow beam of ions. This beam passes between two plates P_1 and P_2 , between which an electric field is maintained.

The effect of an electric field on a stream of ions is to

deflect them, the amount of deflection depending upon the energy of the ions. All those of the same energy are deflected to the same degree; hence all of those which reach and pass through the small hole in the diaphragm have almost the same energy. Those with larger or smaller energy miss the hole because they are deflected too much or too little to score the necessary bull's-eye.

The ions emerging from the hole in the diaphragm have, then, the same energy. But the energy of a moving body depends on its mass and its velocity; hence if a lighter body and a heavier one have the same energy, the former must be travelling faster than the second. The beam of ions now passes through a magnetic field, the direction of which must be supposed to be into or out of the page. A magnetic field also deflects charged particles; but here the deflection depends upon the velocity of the body: the faster it is going, the more it is deflected. It follows that the paths of the lighter ions are more sharply curved than those of the heavier. The instrument can be so adjusted that all of the lighter ions (light isotope) reach one point on the surface of a photographic plate and all of the heavier ions (heavy isotope) another point. If there are three or more isotopes present their ions will arrive at three or more distinct points and record themselves. In its laboratory form the mass spectroscopy is calibrated in such a way that the weights or mass numbers of the isotopes are accurately indicated by the position of their records on the plate.

2. THE GEIGER-MULLER COUNTER

This is an instrument used for recording the arrival of charged particles—electrons, protons, or alpha particles—or of bursts of gamma radiation. It consists (Fig. *App.2*) of a metal cylinder in the middle of which is a thin filament, the two being insulated from one another. The

cylinder is sealed into a glass bulb filled with a gas such as argon at low pressure. Between the filament and the walls of the chamber an electrical pressure, or potential difference, is maintained which is just not sufficient to cause a flash-over through the gas to occur. In the end of

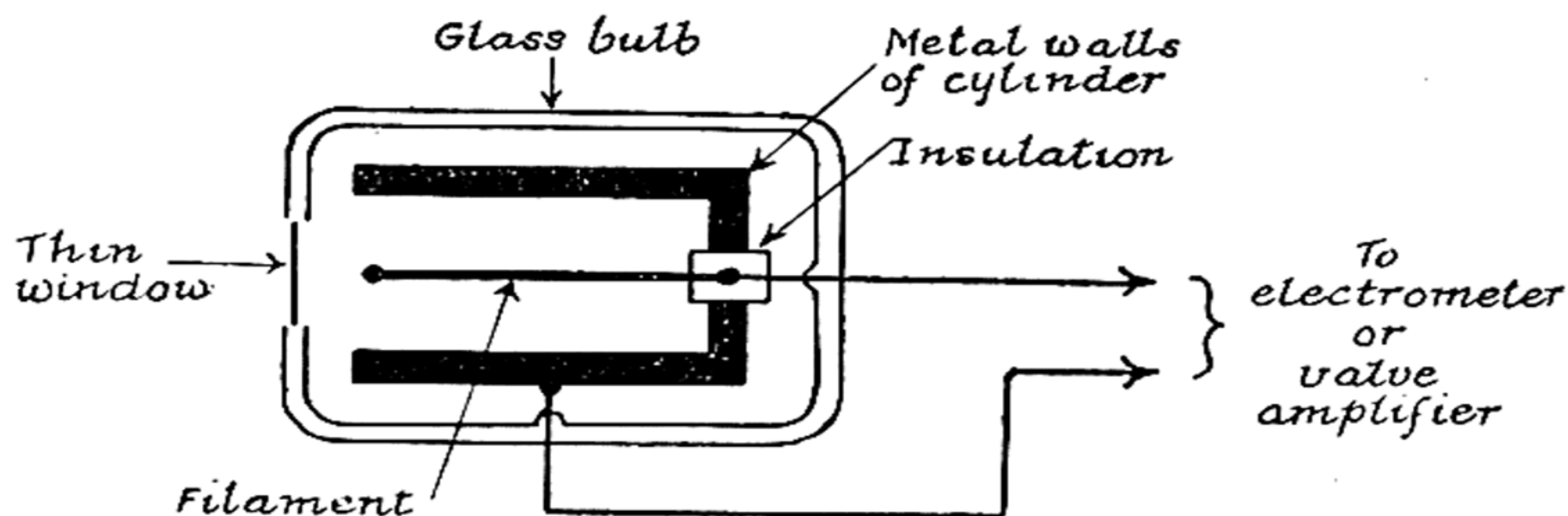


FIG. APP.2. Simplified drawing showing how the Geiger-Muller counter is constructed. This is one of the most useful of the atomic physicist's tools.

the glass bulb which is opposite the open end of the cylinder is a thin "window" of mica, through which charged particles or gamma rays can enter. Suppose that the counter is being used to record the arrival of alpha particles. Each particle coming in through the window ionises the gas, making a conducting path between the filament and the chamber walls. For an instant current flows through the gas between the two. If an electrometer is used to record the passage of a current from filament to cylinder the observer receives a visual indication of the arrival of each particle and can count the number entering the window in a given time—provided that arrivals do not follow one another too rapidly for him to keep pace with them. Another method of counting is to apply the output of the instrument *via* a valve amplifier to a loudspeaker. Each particle then registers its arrival by producing a sound like that of sharply tapping a small drum.

Early investigators did their counting by eye or by ear in these ways. But either was a very tiring business demanding close and sustained attention. Nowadays, the Geiger-Muller apparatus is usually yoked through a valve amplifier to an electronic counting apparatus, which not only does away with the drudgery, but also counts arriving particles, or bursts of gamma radiation at a far greater rate than human eye, ear, or brain can accomplish. The Geiger-Muller instrument can be made to reset itself and be ready for action again in less than a millionth of a second and electronic counters find no difficulty in dealing with events which happen a million times a second.

3. THE COCKCROFT AND WALTON VOLTAGE MULTIPLIER

Soon after his first successful experiments in the transmutation of elements by bombarding the nuclei of their atoms Rutherford realised that he must be able to use projectiles of far greater energy than those then available if he was to obtain the results that he wanted. Till then his only ammunition had been streams of alpha particles from natural sources, such as uranium and radium. He wanted an artificial means of producing streams of particles, travelling at higher speeds than those provided by nature and therefore having greater energy. It will be recalled that the energy of charged particles like the electron, the proton and the alpha particle is measured in electron-volts. Electrons can be speeded up by offering them a target charged to a high positive potential; the higher this potential, the greater the speed that they acquire and the greater their energy. Similarly, protons and alpha particles, having positive charges, may be accelerated by using high negative potentials to pull them. What Rutherford asked for and what two of his

famous team provided was a simple means of converting the two-hundred odd volts of electric mains supplies into hundreds of thousands of volts.

The assistants in question were J. D. Cockcroft (now Sir John Cockcroft) and E. T. S. Walton. Their solution was the famous "ladder" voltage multiplier shown diagrammatically in Fig. *App.3*. This instrument is still largely employed in nuclear physics laboratories and an adaptation of its principle is used in many television receivers to furnish the "extra-high tension" voltage needed for the operation of the cathode-ray tube.

Alternating current, such as is supplied by most domestic lighting and power mains, consists of a series of cycles, in which the current alternates, or changes its direction. It flows in one direction in the first half of each cycle and in the opposite direction in the second half. With such a current the voltage can easily be increased by the use of a device called a transformer. But the increase possible is quite limited, if the instrument is not to be bulky, and heavy—and very expensive. The ladder multiplier has none of these drawbacks. It consists simply of an arrangement of condensers (I use the familiar term rather than the more strictly correct one, capacitors) and rectifiers. One function of a condenser is to store electricity. Let current at a pressure of 1,000 volts flow into it and when it is full (or in electrical parlance "charged") it acquires and retains a potential of 1,000 volts. A rectifier is a simple and inexpensive piece of electrical apparatus which permits only a one-way flow of electric current to take place through it. Thus, if alternating current is applied to a rectifier, one half-cycle causes a flow to take place, whilst in the next there is no flow at all.

Look now at Fig. *App.3* (a). The transformer steps up the 200-volt mains current through its primary to 1,000

volts in its secondary. In one half-cycle current flows through the rectifier *Rect 1* into the condenser C_1 and charges it to 1,000 volts. In the next half-cycle the direction of current reverses; nothing flows into or out of C_1 ,

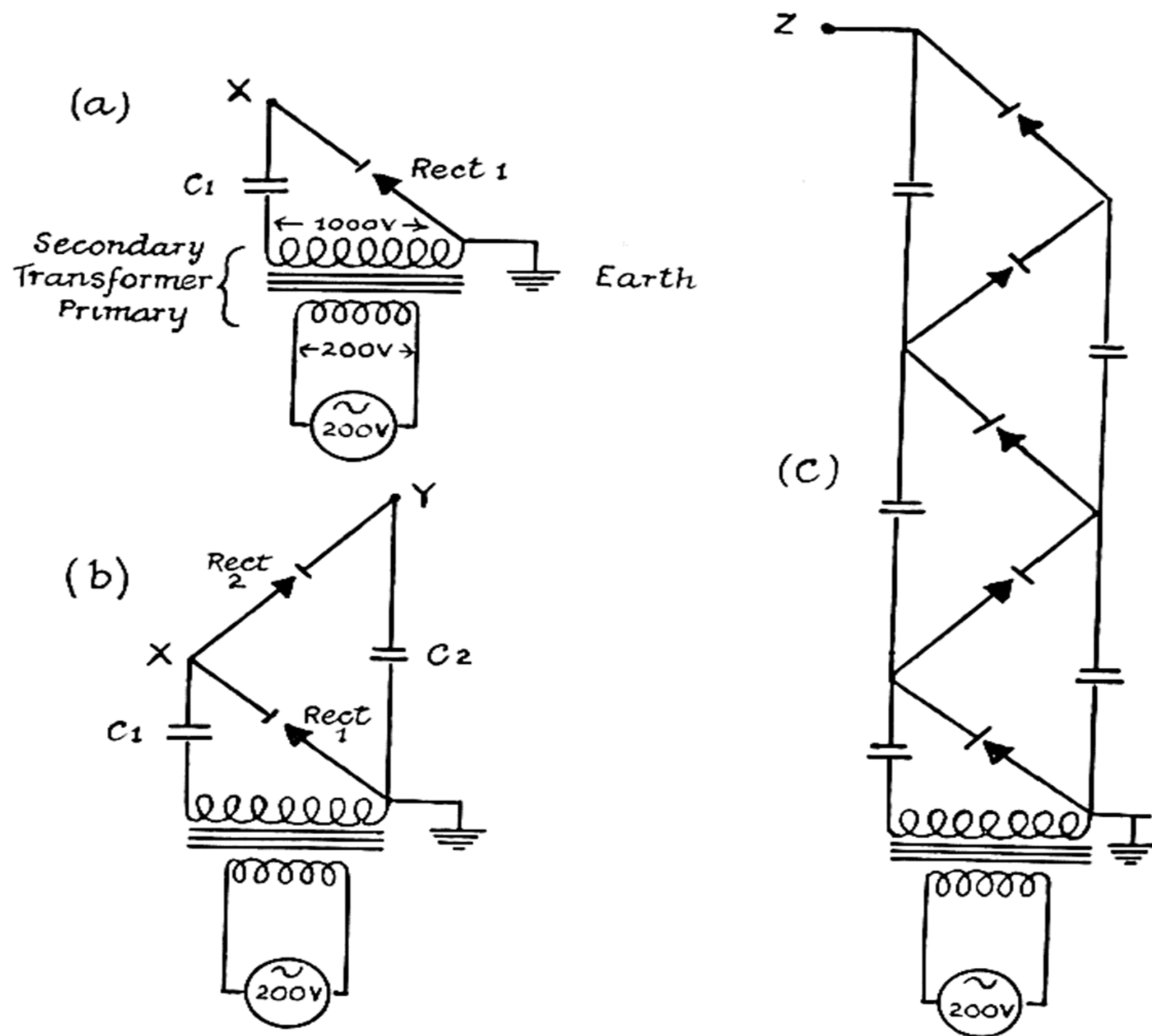


FIG. APP.3. The Cockcroft and Walton "ladder" voltage multiplier. As explained in the text, the device may be used to convert a mains voltage of some 200 volts to a potential of hundreds of thousands of volts. A modified form of the ladder is used in many domestic television sets to furnish the 5,000–6,000 volts needed for "painting" the pictures on the screen.

which remains charged at 1,000 volts. There is thus a potential difference of 1,000 volts between the point X and earth. Along comes the next half-cycle. Current can

again flow through *Rect 1* and the potential between the point *X* and earth is now the thousand volts stored in the condenser plus the thousand volts brought in by this flow of current. There can be no "backlash" for the rectifier allows no flow of current in the opposite direction. Hence *X* continues to have a potential 2,000 volts different from earth. If we call the potential across the transformer secondary V , then that at *X* is twice this amount, or $2V$.

Let us go a step further by adding another rectifier and another condenser (Fig. *App.3 (b)*). During a half-cycle, when *Rect 1* will not allow current to pass from the transformer, *Rect 2* offers no obstacle to current from *X* and *C2* becomes charged to the potential of *X*, or $2V$. The next half-cycle, when both *Rect 1* and *Rect 2* pass current, brings the point *Y* to the potential of *C2* plus that brought in by this half-cycle. The potential at *Y* is thus $2,000 + 1,000 = 3,000$ volts, or $3V$. Adding further rungs to the ladder, as in Fig. *App.3 (c)*, we obtain at point *Z* a potential of $6V$. The original mains voltage of 200 has been multiplied five times by the transformer and a further six times by the ladder. The potential difference between *Z* and earth is $200 \times 5 \times 6 = 30$ times the original mains voltage. Actually, the difference of potential between *Z* and earth is not quite 6,000 volts, for some of the electrical pressure is used up in driving current through the rectifiers and the wiring and into the condensers. But an increase of very nearly thirty-fold is realised and the ladder can be extended until potentials of hundreds of thousands of volts are obtainable at its top.

4. THE BETATRON

If we wish to increase the energy of a charged particle, we must raise the velocity at which it travels. The energy of a moving body is $\frac{1}{2}mv^2$, where m is its mass, or weight,

and v its velocity. From this it follows that if the velocity is doubled, the energy is increased 2^2 , or 4 times. Treble the velocity and you increase the energy nine times; impart four times the velocity and the energy is increased 4^2 , or 16 times. When the velocity becomes high enough to bear some comparison with that of light (186,200 miles, or 300,000,000 metres a second), Einstein's law of the increase of mass with velocity begins to be important. Up to that point its results are negligibly small and can be disregarded.

The application of a high voltage of appropriate sign (positive voltage to a negatively charged particle; negative voltage to one carrying a positive charge) is only one way of securing the desired acceleration. Devices such as the Cockcroft and Walton ladder voltage multiplier produce an electric field; and, as we have seen, a charged particle, "falling through," or drawn across such a field (Fig. *App.4 (a)*) by the attraction of the electrical potential difference, acquires an energy of a number of electron-volts which depends upon the pull exercised by the electrical pressure, or voltage. The higher the voltage, the greater is the velocity (and therefore the energy) imparted to charged particles introduced into an electric field. In Fig. *App.4 (a)* if a 100-volt battery is used the electron acquires an energy of 100 eV.

But there is another kind of field which can exercise an important influence on a charged particle. This is the magnetic field; the effect of which on an electron is seen in Fig. *App.4 (b)*: an electron introduced into a magnetic field tends to take a circular path at right angles to the direction of the field. If the strength of the field is rising the electron undergoes acceleration as it travels in such a path.

Suppose now that an alternating current is applied to the windings of the electro-magnet in Fig. *App.4 (b)*. In

each half-cycle current rises from zero to maximum and then falls back to zero. In the first quarter of the cycle it is rapidly increasing and an electron in the magnetic field would be accelerated. It is this quarter-cycle which is

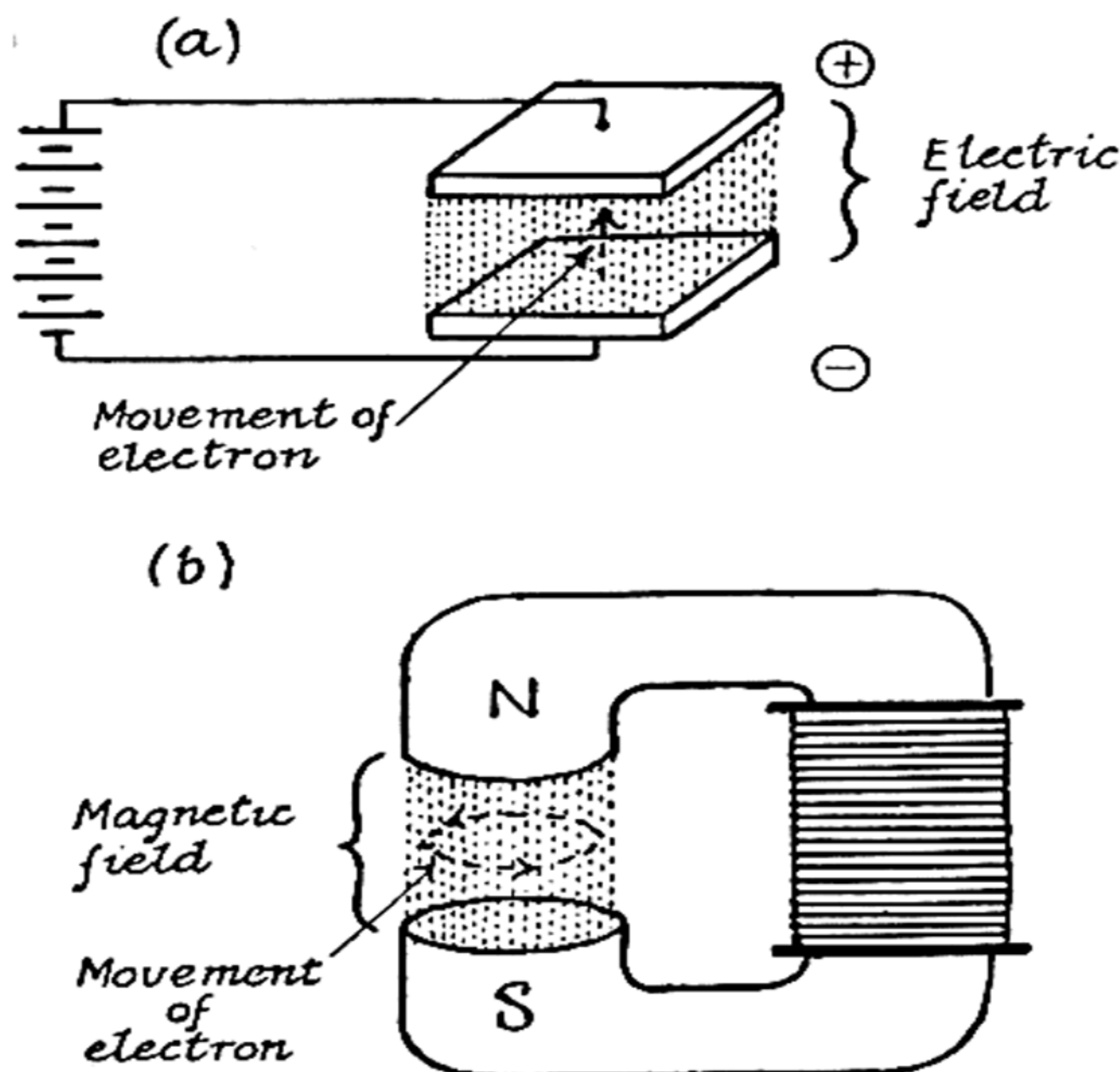


FIG. APP.4. (a) A charged particle drawn across an electric field by a potential of opposite sign to its own acquires an amount of energy which depends upon the magnitude of the potential exercising the pull. (b) A charged particle introduced into a magnetic field is caused to move in a circular path.

made use of in the Betatron, a device so called because it is designed to accelerate beta particles, or electrons.

The circular evacuated glass tube seen in Fig. App.5 must be imagined as lying between the poles of a very powerful electro-magnet, one pole being below the page and the other above it. Electrons, already accelerated to some 50,000 eV by the electric field between the anode and cathode of the "gun" are shot into the tube just as a rising quarter-cycle of current through the magnet

windings begins. They then travel round and round the tube, gaining some hundreds of electron-volts of energy at each revolution. As hundreds of thousands of revolutions may be made during the quarter-cycle of current, the total energy acquired may reach from 50 to 250 million eV.

The Betatron may be used as a very powerful X-ray

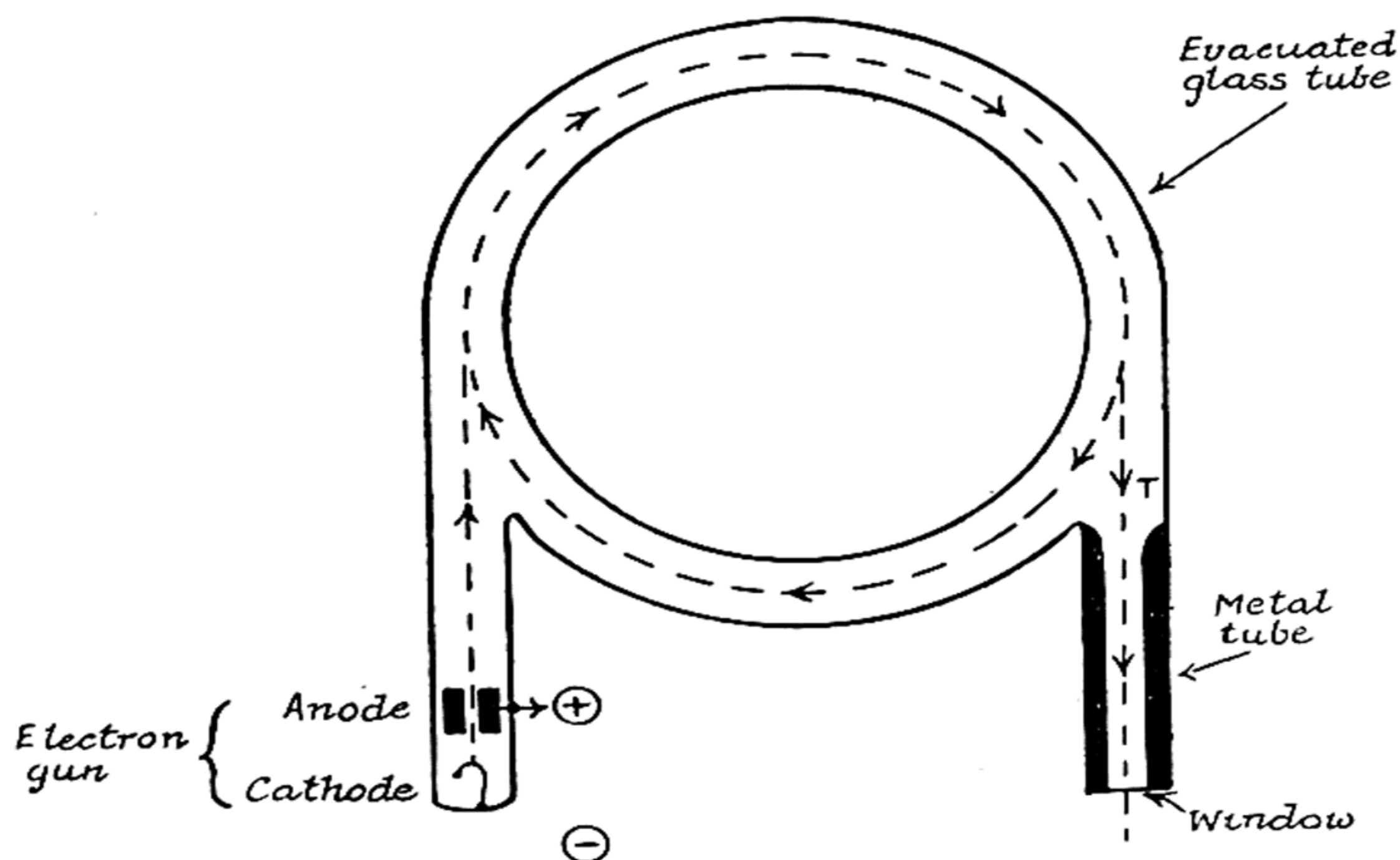


FIG. APP.5. The principle of the betatron. Electrons "fired" by the "gun" into the tube are made by the increasing intensity of the magnetic field (which must be imagined to have a direction at right angles to the page) to describe circular paths at higher and higher speeds. They thus acquire greatly increased energy. If a target is placed at *T*, electrons strike it and cause the emission of very penetrating X-rays. When there is no target high-energy electrons are delivered through the window.

tube. In that case a "target" is placed at *T* in the drawing. The electrons are deflected from their circular path just as the magnetic field is at its strongest. Their impact on the target causes the emission of very penetrating radiation. If, on the other hand, the electrons are wanted as missiles for nuclear bombardment, the target is not used.

Instead, the electrons are diverted into the metal tube and stream out through the window at the end.

5. THE CYCLOTRON

The Betatron is a comparatively small instrument; the Cyclotron, used for the acceleration of much heavier charged particles, such as deuterons and helium nuclei, may incorporate an electro-magnet weighing several hundred tons. In the Cyclotron acceleration is again obtained, though in rather different ways, by means of electric and magnetic fields. The key components of the device (Fig. App.6) are two semi-circular metal boxes,

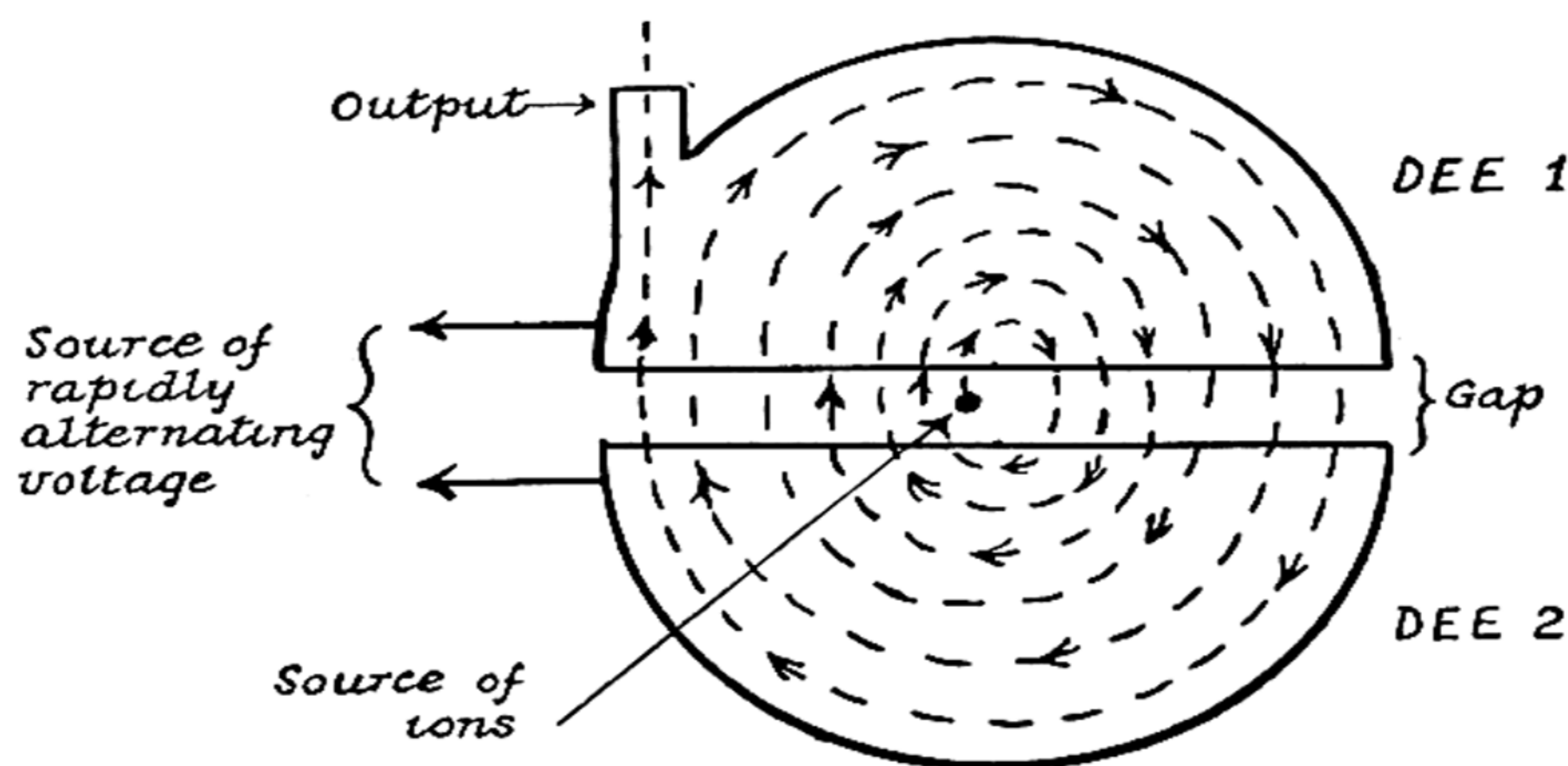


FIG. APP.6. The principle of the cyclotron. The charged particle describes an increasing spiral path, gaining energy at each half-revolution. When it reaches the output the particle may have an energy of 20 MeV.

called Dees on account of their shape. These are arranged with their open ends facing one another and with a gap between them. In the gap, near the centres of the Dees, is a source of ions. The Dees are connected to a source of rapidly alternating voltage, so that during one half-cycle *Dee 1* is positively and *Dee 2* negatively charged, the charges being reversed in the next half-cycle. The Dees

are sealed into an evacuated container placed (in the same way as the tube of the Betatron) between the poles of an electro-magnet.

Suppose that a proton is delivered by the ion source at the instant when *Dee* 1 is negative and *Dee* 2 positive. The particle is attracted into *Dee* 1, where the magnetic field causes it to describe a semi-circular path. At the end of this it again reaches the gap; but by now *Dee* 2 has become negative and the proton is pulled across the gap and into this *Dee*. During its journey from the gap to *Dee* 1 the particle was accelerated in the electric field due to the potential difference of, say, 10,000 volts between the Dees and acquired an energy of 10,000 eV. In crossing the gap to *Dee* 2 it gains another 10,000 electron volts of energy. It continues to make revolutions, passing from one *Dee* to the other and gaining 20,000 eV of energy at each complete revolution. Its velocity thus rises rapidly, and, owing to the effects of centrifugal force (special arrangements are made in the Betatron to counteract these) its path takes the form of an increasing spiral. The semi-circular (or almost semi-circular) paths are all accomplished in the same time, but they become larger and larger with the increased velocity of the particle. After some hundreds of revolutions the particle is deflected to the output of the tube, where it may have an energy of 20 million eV.

6. THE SYNCHROTRON

It will be realised that the successive accelerations in the Cyclotron can take place only if the particle always arrives at the gap at exactly the right instant: it must, so to speak, keep in step with the rapid alternations of the electric field. These conditions can obtain only so long as the velocity of the particle is insufficient to bring about an appreciable increase in its mass in accordance with

Einstein's law. There is thus a very definite limit to the velocity (and therefore to the energy) that can be imparted to ions of any kind in a Cyclotron. This is about 20 million eV. Above that figure the increase in mass slows down the particles and makes them lag behind the changes in the electric field.

The Synchrotron, or Synchrocyclotron, does not provide a means of dodging the consequences of Einstein's law that the mass of a rapidly moving body is increased. It goes much further: it actually makes use of that increase. The fact that the instrument works is a remarkable demonstration of the validity of the law in question. It was designed purely on the assumption that Einstein was right. If he were wrong, it could not work; if he were right, it must work. It does work and so far as we can see, it proves to the hilt the truth of this revolutionary idea advanced by Einstein.

The construction of the Synchrotron is very like that of the Cyclotron. There are the same Dees, lying in the same kind of constant magnetic field. But there is one big difference: the frequency of the alternating voltage which gives rise to the electric field is made to rise rapidly. And the increase in the mass of the particle undergoing acceleration is made to keep it exactly in step, or to synchronise it, with the increasingly rapid voltage changeovers. Hence the name Synchrotron.

Suppose that in one Dee a particle is so accelerated that it would, if its mass remained unaltered, arrive at the gap a little in advance of the voltage change. It would then be slowed down and lose energy by being repelled by a charge of the wrong sign on the opposite Dee. Or, suppose that it got there a tiny fraction of a second too late, after the voltage change had occurred. It would then miss an important part of the accelerating pull that the voltage on the other Dee should impart.

What actually happens in the Synchrotron is that if a particle acquires a speed which would bring it to the gap too soon, the increase in its mass owing to this speed makes it take a little longer to complete its semi-circle in the Dee. On the other hand, should it be travelling too slowly, its mass decreases and its velocity goes up accordingly. The result is that the variation of mass with speed, coupled with the corresponding variation of speed with mass, locks the velocity of the particle at any instant to the frequency at which the electric field changes.

If it is behind time it is speeded up by loss of mass; should it be ahead of schedule, it is slowed down by increased mass.

The Synchrotron can provide missiles of enormous energy and in quantities far surpassing those from natural sources. It is one of the most potent tools in the laboratories of the detectives of science, for it supplies a purely artificial means of transmuting elements which far transcends any furnished by nature.

Some idea of the size and the possibilities of the Synchrotron may be formed when it is mentioned that one of the latest has a magnet weighing nearly 4,000 tons and it is itself a good deal bigger than an average house.

APPENDIX

PERIODIC TABLE

Period	GROUP I	GROUP II	GROUP III	GROUP IV	GROUP V
1	HYDROGEN H=1.0078 No. 1				
2	LITHIUM Li=6.940 No. 3	BERYLLIUM Be=9.02 No. 4	BORON B=10.82 No. 5	CARBON C=12.00 No. 6	NITROGEN N=14.008 No. 7
3	SODIUM Na=22.997 No. 11	MAGNESIUM Mg=24.32 No. 12	ALUMINIUM Al=26.97 No. 13	SILICON Si=28.06 No. 14	PHOSPHORUS P=31.02 No. 15
4	POTASSIUM K=39.10 No. 19	CALCIUM Ca=40.08 No. 20	SCANDIUM Sc=45.10 No. 21	TITANIUM Ti=47.90 No. 22	VANADIUM V=50.95 No. 23
	COPPER Cu=63.57 No. 29	ZINC Zn=65.38 No. 30	GALLIUM Ga=69.72 No. 31	GERMANIUM Ge=72.60 No. 32	ARSENIC As=74.93 No. 33
5	RUBIDIUM Rb=85.44 No. 37	STRONTIUM Sr=87.63 No. 38	YTTRIUM Y=88.92 No. 39	ZIRCONIUM Zr=91.22 No. 40	NIOBIUM N=93.3 No. 41
	SILVER Ag=107.880 No. 47	CADMIUM Cd=112.41 No. 48	INDIUM In=114.8 No. 49	TIN Sn=118.70 No. 50	ANTIMONY Sb=121.76 No. 51
6	CAESIUM Cs=132.81 No. 55	BARIUM Ba=137.36 No. 56	RARE EARTHS Nos. 57-71	HAFNIUM Hf=178.6 No. 72	TANTALUM Ta=181.4 No. 73
	GOLD Au=197.2 No. 79	MERCURY Hg=200.61 No. 80	THALLIUM Tl=204.39 No. 81	LEAD Pb=207.22 No. 82	BISMUTH Bi=209.00 No. 83
7	No. 87	RADIUM Ra=225.97 No. 88	ACTINIUM Ac=227.02 No. 89	THORIUM Th=232.12 No. 90	PROTOACTINIUM Pa=231.03 No. 91

THE RARE			
LANTHANUM La=138.00 No. 57	CERIUM Ce=140.10 No. 58	PRASE- ODYMIUM Pr=140.92 No. 59	NEODYMIUM Nd=144.27 No. 60
TERBIUM Tb=195.2 No. 65		DYSPROSIUM Dy=162.46 No. 66	HOLMIUM Ho=163.5 No. 67

B

OF THE ELEMENTS

GROUP VI	GROUP VII	GROUP O	GROUP VIII		
		HELIUM He=4.002 No. 2			
OXYGEN O=16.000 No. 8	FLUORINE F=19.00 No. 9	NEON Ne=20.183 No. 10			
SULPHUR S=32.06 No. 16	CHLORINE Cl=35.457 No. 17	ARGON A=39.944 No. 18			
CHROMIUM Cr=52.01 No. 24	MANGANESE Mn=54.93 No. 25		IRON Fe=55.84 No. 26	COBALT Co=58.94 No. 27	NICKEL Ni=58.69 No. 28
SELENIUM Se=79.2 No. 34	BROMINE Br=79.916 No. 35	KRYPTON Kr=82.9 No. 36			
MOLYBDENUM Mo=96.0 No. 42	TECHNETIUM No. 43		RUTHENIUM Ru=101.7 No. 44	RHODIUM Rh=102.91 No. 45	PALLADIUM Pd=106.7 No. 46
TELLURIUM Te=127.5 No. 52	IODINE I=126.932 No. 53	XENON Xe=130.2 No. 54			
TUNGSTEN W=184.0 No. 74	RHENIUM Re=186.31 No. 75		OSMIUM Os=190.8 No. 76	IRIDIUM Ir=193.1 No. 77	PLATINUM Pt=195.23 No. 78
POLONIUM Po=209.99 No. 84	No. 85	RADON Rn=222 No. 86			
URANIUM U=238.14 No. 92					

EARTH ELEMENTS

ILLINIUM Il=146.(?) No. 61	SAMARIUM Sm=150.43 No. 62	EUROPIUM Eu=152.0 No. 63	GADOLINIUM Gd=157.3 No. 64
ERBIUM Er=167.64 No. 68	THULIUM Tm=169.4 No. 69	YTTERBIUM Yb=173.5 No. 70	LUTECIUM Lu=175.0 No. 71

NEW ELEMENTS

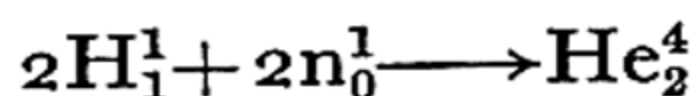
93 NEPTUNIUM,
Np. At. Wt. 239
94 PLUTONIUM,
Pu, At. Wt. 239
95 AMERICIUM,
Am.
96 CURIUM, Cm.

APPENDIX C

The Hydrogen Bomb

WE SAW IN CHAPTER IX (p. 90) that the light and the heat radiated by the sun and other stars are believed to result from the continual conversion on a vast scale of hydrogen into helium. Notice particularly that the building *up* of the more complex helium nucleus from a combination of protons (hydrogen nuclei) and neutrons is the exact opposite of what takes place in the atomic pile and in the uranium bomb. In both of the latter energy is released by the fission of a very complex nucleus, in which it is broken *down* into the nuclei of other elements, lower in the scales both of atomic numbers and of atomic weights.

In the building-up process believed to take place in the sun two hydrogen nuclei combine with two neutrons to form the two-proton, two-neutron nucleus of helium. In shorthand notation the process is:



Energy is released when fission of a uranium nucleus occurs because the weight of the nuclei produced by the splitting is less than that of the original uranium nucleus added to that of the neutron whose arrival set things going. In a word, there is less matter in existence *as matter* after fission than before it: the "missing" matter has been converted into its other form, energy.

If we add together the weights of a nucleus of U_{92}^{235} and a neutron and subtract from the total the combined weights of the fission products—nuclei and ejected neutrons—we find that approximately 0.08 per cent. of

the original mass has been "lost." This loss represents the percentage of the original matter which appears in the form of energy. Were a 350-lb. uranium bomb one hundred per cent. efficient (which it is very far from being, for reasons given on page 138), the total weight of matter converted into energy would be some 4 ounces. The bomb which devastated Hiroshima had an efficiency no greater than 10 per cent., which means that the appalling effects then produced were due to the conversion into energy of at most 0.4 ounce of matter—the weight of about ten cigarettes. Thinking on this, one begins to realise dimly how immense is the energy bound up in even the smallest speck of matter.

The building up of a helium nucleus from those of hydrogen results also in a loss of weight and a release of energy. But in this instance the difference between the weight of the helium nucleus produced and that of the original hydrogen nuclei and neutrons is about three times as great. Instead of 0.08 per cent. of the original matter converted into energy we now have 0.23 per cent.

Then, why bother any more about uranium, which is far scarcer than gold? Hydrogen is one of the commonest of all elements; two atoms, for instance, out of every three in all the seas, lakes and rivers of the world are hydrogen atoms. Why not use hydrogen as the source of all the energy that Man needs?

On pp. 119 and 120 we saw that one of the earliest results achieved with the Cockcroft and Walton high-voltage apparatus was the production of helium by bombarding lithium with fast-flying hydrogen nuclei. For reasons given on p. 120 this process could not be in itself a useful source of energy.

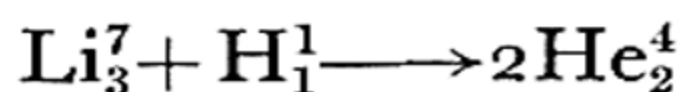
Nevertheless, it gave the first inkling of the means whereby energy might be produced by Man on a colossal scale. Large quantities of hydrogen can be made to build

up into helium if another form of energy—heat—is applied. The heat required is about equal to that at the centre of the sun, some 20 million degrees centigrade.

Until quite recently, it was thought impossible for Man to produce such terrific temperatures. But when the first uranium bomb exploded it was found that they had been realised and even considerably exceeded.

There are several ways in which the temperatures now obtainable from the fission of uranium might be used to produce helium from hydrogen with a vastly greater release of energy. One of the simplest and the most efficient is to apply this heat to a mass of the compound lithium hydride, LiH , which is readily and cheaply available in large quantities. The molecule of lithium hydride is a partnership of one atom of lithium Li_3^7 with one atom of hydrogen H_1^1 .

At very high temperatures a reshuffling of the protons and neutrons takes place. There are four of each, eight particles in all, with four positive charges. The particles rearrange themselves into two similar combinations, each containing two protons and two neutrons and having two positive charges. Any such combination of protons and neutrons can be one thing and one thing only—a helium nucleus. Thus one molecule of hydrogen and one of lithium hydride are turned into two atoms of helium. In shorthand form:



In the process 0.23 per cent. of the lithium hydride is converted into energy. In other words, the changing of 1,000 lb. of lithium hydride into helium means that 2.3 lb. of matter take the form of energy, if the process is one hundred per cent. efficient. And there seems to be no particular reason why something approaching this efficiency should not be reached, for we are here con-

cerned not with the mean free paths of neutrons (pp. 135-8) but with temperatures.

Recalling what the conversion of less than half an ounce of matter into energy did at Hiroshima, you may picture in imagination what would happen if it was a question not of fractions of an ounce, but of pounds. Nor is there any apparent reason why a limit should be set in pounds—or even in hundredweights. Lithium hydride, unlike uranium, is perfectly stable. Tons of it could be packed into a bomb, without there being any risk of the spontaneous disintegration discussed on p. 136.

In the construction of a hydrogen bomb a 350-lb. uranium bomb might play much the same part as the cap of a gun or rifle cartridge. When the cap is struck it fires and projects an intensely hot flame into the powder charge, causing an explosion to take place.

Imagine a uranium bomb fixed in the middle of a metal case containing, say, two tons of lithium hydride. When the uranium explosion takes place the enormous heat generated brings about a vastly more violent explosion by triggering off the conversion of the mass of lithium hydride into helium. Instead of a mere four-tenths of an ounce, we now have the possibility of the conversion of some 10 lb. of matter into energy.

There appears to be no possibility of applying the energy released in this way by the build-up of hydrogen into helium to any but destructive purposes. So far as we now know the temperature required can be obtained only from the uncontrolled release of energy due to uranium or plutonium fission. Nor does there seem to be any means of controlling the energy released when helium is subsequently produced.

To make bigger and bigger bombs is a matter of engineering rather than of physics. The uranium bomb has destroyed cities: it is no exaggeration to say, as one

writer has said, that the hydrogen bomb makes it possible for a single nation with ordinary industrial resources to destroy civilisation.

One cannot help being reminded of the parable of the Garden of Eden. Man has eaten the fruit of the Tree of Knowledge and has at his command the power of doing either much good by applying atomic energy to entirely peaceful purposes, or incalculable evil by misapplying it to horrible ends. We must hope and pray that he will not misuse his knowledge, now that he so nearly knows the answer to the age-old question: What is matter? . . . Or does he?



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Index

- AIR, a mixture of gases, 16
 Alchemists, 12, 13
 Alpha particle, 37, 40, 60; thence *passim*.
 Anderson, C. D., 109
 Animals, breathing of, 16, 17
 equipment by Nature, 6, 7
 limited habitats of species, 6, 7
 Aristotle, 10, 11
 Aston, F. W., 74, 173-5
 Atom, Bohr's picture of, 82-7
 combinations of, 18
 modern ideas of, 14
 neutral state of, 37
 Rutherford's conception of, 38-44
 Atomic bomb, hydrogen, 190 *et seq.*
 uranium, 134-40
 Atomic numbers, 46, 48, 49, 101
 Atomic pile, *see* Pile, atomic
 Atomic weights, 19, 20, 23-7
 Avogadro, 20-2
- BETA particle, 37, 60
 Betatron, 180-4
 Bohr, Nils, 81-7
 "Breeding" fissile material, 167
- CADMIUM regulator in atomic pile, 132
 Carbon moderator in pile, 131
 Cathode-ray tube, 30-3
 Cavendish, Henry, 13, 14
 Cavendish Laboratory, 13, 68
 Chadwick, Sir James, 67-70
 Chain reactions, 118-33
 Chemists, 45-58
 Cloudchamber, 63-6, 69, 70, 115
 Cockcroft, Sir J. D., 119, 177-80
 Cockcroft and Walton apparatus, 119, 177-80
 Combustion, 16, 18, 19, 54, 144, 145
 Compound, meaning of, 14, 15
 Conductor, electric, 112
 Cosmic rays, 114-16
 Crookes, Sir W., 29
 Curie, Professor and Madame, 35, 36
 Cyclotron, 184-5
- DALTON, 14, 19
 Democritus, 10
- Detonation, 145, 146
 Deuteron, 168
- EINSTEIN, 81, 120
 Theory of mass and energy, 90-93
 Electric field, 30-3, 92, 93, 135, 173-5, 181-7
 Electrolysis, 54
 Electron, charge of, 33
 discovery of, 28
 mass of, 33
 orbiting, 38 *et seq.*, 82-7
 and radiation, 79-87
 Electron-volt, 92
 Element, alchemists' ideas about, 13
 Aristotle's views on, 9
 early conceptions of, 9
 modern definition of, 14, 15
 trace and tracer, 163, 164
 Energy, conservation of, 55, 93
 Euclid, 2
 Explosion, 145
- FISSION of nucleus, 122-5, 129, 133, 135-40, 168, 169
 Frequency, 80
- GAMMA rays, 37, 60, 110
 Geiger-Müller counter, 175-7
- HAHN, discoverer of nuclear fission, 122, 123
 Half-life, 99, 100
 Holmes, Sherlock, 3, 24
- INSULATORS, electric, 122
 Ion, meaning of, 40
 Ionisation, 51, 52, 111
 Isotopes, 73-7, 95-7
 light and heavy, 95
 radio-active, 95, 157, 158, 161-5
- JEANS, Sir J. H., 42, 88
- LAVOISIER, 14
 Lithium, bombardment of protons, 119
 use in hydrogen bomb, 190 *et seq.*
 Lodge, Sir O., 28

- MAGNETIC field, 31-3, 173-5, 181-7
 Man, desire for knowledge, 8-10
 equipment invented by, 7
 natural equipment, 6
 Mass-energy, conservation of, 93
 Mass number, 74
 Mass spectrograph, 173-5
 Matter, conservation of, 19, 55, 78, 93
 Mean free path, 135, 136
 Mendeleev, 46
 Meson, 115-17
 Moderator, in atomic pile, 131, 148, 149
 Moseley, H. G. J., discovers significance of atomic number, 48

 NATURE, equipment of man and animals, 6-8
 Neptunium, 130
 Neutrino, 117
 Neutron, discovery of, 69; thence *passim*
 Newton, Sir Isaac, 80
 Nova or New Star, 140
 Nucleus, bombardment of by Rutherford, 62-7, 119
 contains nearly all mass of atom, 41
 fission of, 122-5, 129, 133, 135-40, 168, 169
 modern ideas of, 71, 72, 81-93
 nature changed by radio activity, 61
 Rutherford's picture of, 38 *et seq.*

 PERIODIC Table of Elements, 188-9
 work of Mendeleev, 46
 Pile, atomic, 131-3, 148-53, 154-60, 161-5
 Plants, effects of on atmosphere, 16, 17
 Planck, Max, constant, 86
 quantum theory, 80-7
 Plutonium, 130-3; thence *passim*.
 Poirot, 3
 Positron, 109, 110
 Proton, nucleus of hydrogen atom, 38; thence *passim*.
 Protyle, 25, 71
 Prout, William, 25, 71, 89

 QUANTUM, theory, 80-7

 RADIATION, how caused, 79-87
 cosmic, 114-17
 Radio-activity, discovery of, 36
 nature of, 60-2, 94-110
 of fission by-products, 157, 158, 161-5
 Radium, discovery of, 36
 Renaissance, 11
 Röntgen, 34
 Rutherford, Lord, 37, 48, 49, 59 *et seq.*, 68, 71, 118, 119
 conception of atom, 38-44

 SOCRATES, 1
 Symbols, chemical, 14, 15
 Synchrotron, 185-7

 THOMSON, Sir J. J., 29-33, 49
 Thorium, 100-7, 141, 159
 T.N.T., 126
 Transmutation of elements, aim of alchemists, 12
 in physical laboratory, 67, 75, 119, 120
 spontaneous by radio activity, 36
 61, 94-110
 Transparency of matter, 35
 Truth, 1-4

 URANIUM, 60, 95-7
 breakdown into lead, 105-9
 fission of nucleus, 122-5, 129, 133, 135-40
 isotopes 235 and 238, 128
 neptunium and plutonium produced from, 130

 VALENCY, 57, 58

 WALTON, E. T. S., 119, 177-80
 Wavelength, 80
 Wave-mechanics, 82
 White dwarf stars, 42, 88, 89
 Wilson, C. T. R., cloud chamber, 63-6
 Wimsey, Lord Peter, 3

 X-RAYS, discovery of, 34

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